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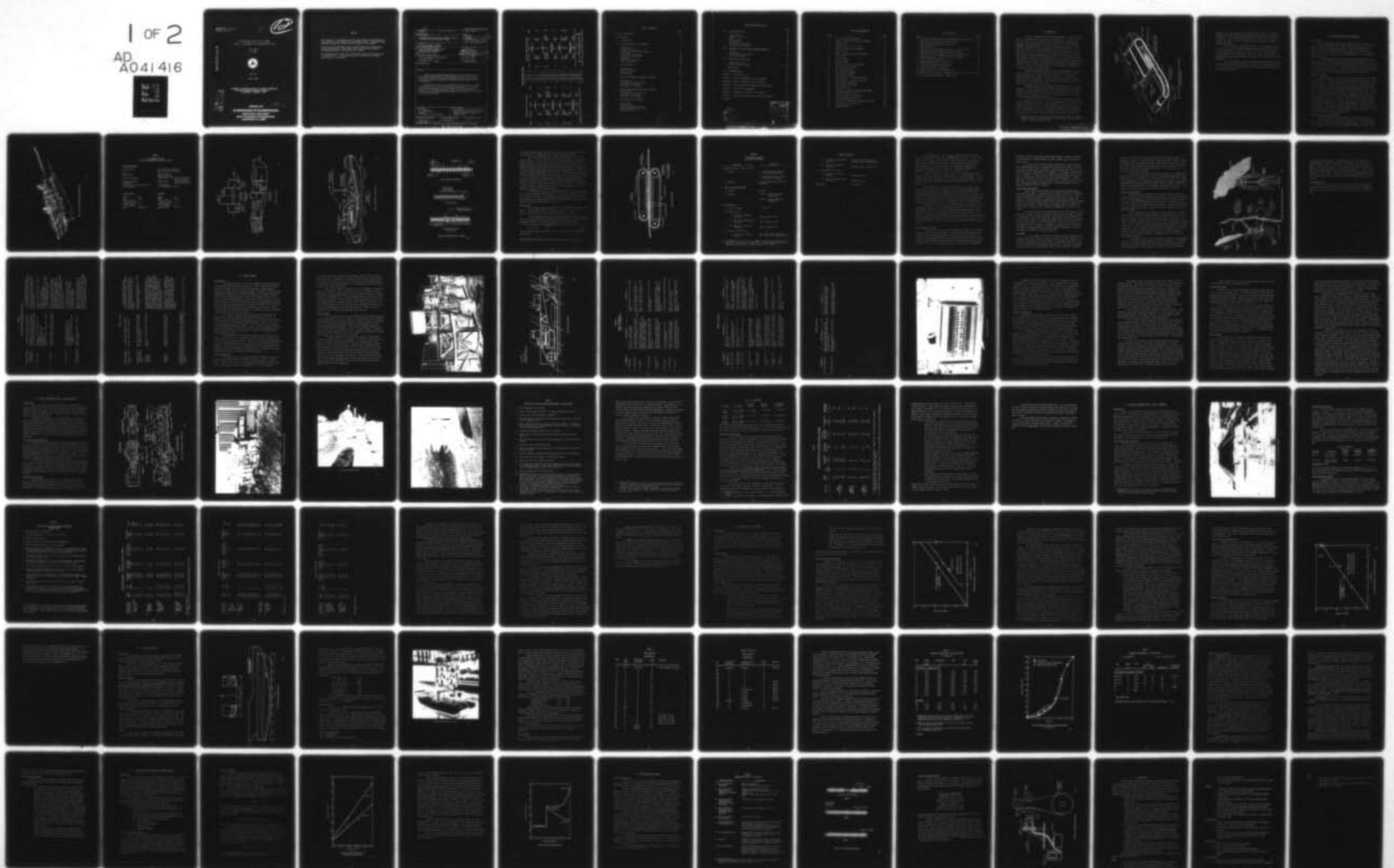

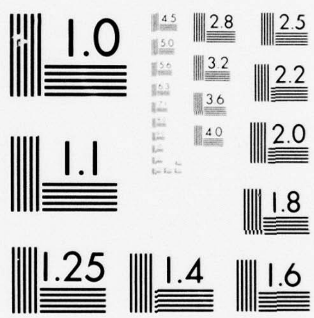

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A ZERO-RELATIVE-VELOCITY BELT SKIMMER
STAGE II - CONFIRMING TESTS AND PROTOTYPE DESIGN

R. R. AYERS
J. M. WARD

DEPARTMENT OF TRANSPORTATION
UNITED STATES OF AMERICA

MAY 1977

FINAL REPORT

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16. Abstract

A 40-foot-long prototype skimming vessel has been designed which uses twin floating sorbent belts to recover spilled oil in 6-8 knot currents. Oil recovery rates up to 600 gpm are possible with the prototype because the composite belts are propelled at the same speed as the water (relative to the vessel).

The performance of this zero-relative-velocity (ZRV) belt arrangement was tow-tested at full scale in calm water and in waves. Also tested for proper motion response was a 1/8-scale model of the catamaran vessel that supports the oil recovery apparatus. Results from the test program were used to aid the prototype ZRV Skimmer design effort and quantify its projected oil recovery performance.

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

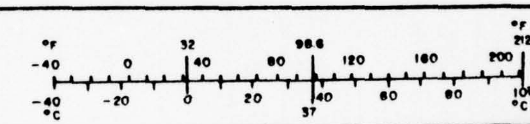

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF ILLUSTRATIONS

LIST OF TABLES

I. INTRODUCTION

The ZRV, developed by Shell Development Company for the U.S. Coast Guard, is a sorbent belt skimmer based on the principle of collecting oil from the water's surface such that there is approximately a zero relative velocity between a moving belt and an oil layer on water. The operating principle, sketched in Figure 1, shows how an endless sorbent belt can be positioned to act like a blanket floating on the water's surface. The belt must contact the oil layer long enough to allow effective sorption of oil. Thus the belt contact length must be much longer than that of conventional belt skimmers and move at a prescribed velocity. If no appreciable velocity difference exists between an oil layer and the removal device, no major turbulence results, and hence, oil droplets associated with the entrainment do not form. Further, if the belt operates in a low-tension configuration, it can conform nicely with surface waves.

The sorbent belt developed for use on the ZRV skimmer is a composite one that will efficiently remove high and low viscosity oils alike during extremely short contact periods (2-4 seconds). The component materials of the belt "sandwich" are an artificial turf material for the outer surfaces of the belt (for viscous oils) and a polypropylene felt as the inner material (for low viscosity oils).

High belt speeds prevent using paired "washing machine" rollers to squeeze oil from this belt because of high belt pore pressures. So paired, chain-driven tank-tread-like plates are used instead and these perforated plates, backed up by rollers, expel oil from the sorbent belt over a five-foot distance, minimizing pore pressures.

Results of Stage I tests[1] simulating the belt and wringer action (when extrapolated to prototype scale) showed maximum oil recovery equivalent to 788 to 1660 gpm for two 3-1/2 foot-wide belts at a speed of 6 knots. There was reasonable concern that these results might be overly optimistic, since large-belt performance was extrapolated from small-belt coupon results. The data from large-scale Stage II testing, reported here, suggests that

1. Ayers, R. R., et al, "A Zero-Relative-Velocity Belt Skimmer", prepared by Shell Development Company for the U.S. Coast Guard, Contract DOT-CG-42229-A. Final Report, April 1975.

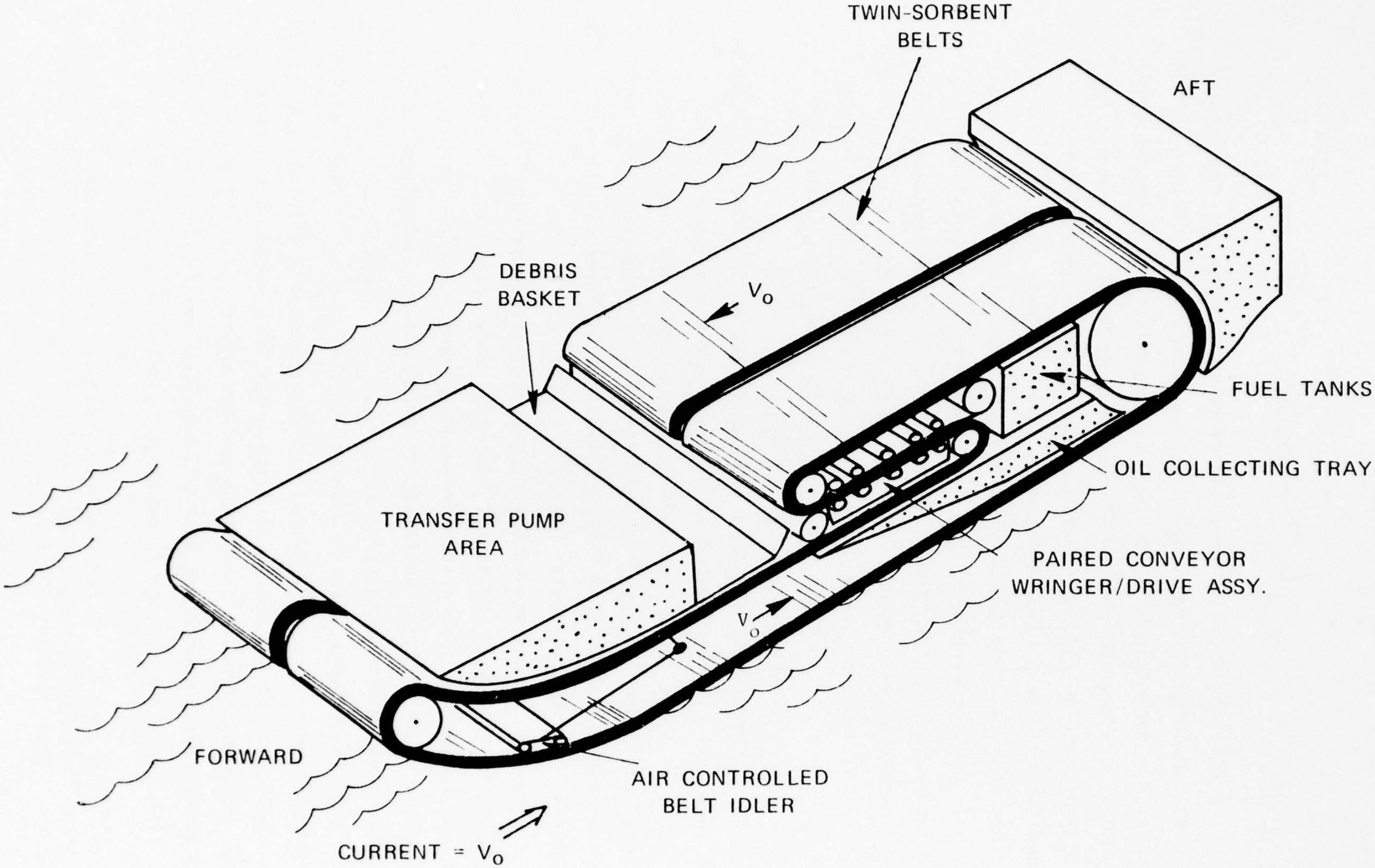

Figure 1. ZRV, A Belt Skimming Concept to Attain Zero-Relative Velocity Conditions in High Currents

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maximum recovery rates from 518 to 595 gpm are more realistic. Regardless, we find that the ZRV skimming concept works; the numerous tests performed confirm that a truly effective prototype skimmer can be built to skim oil in currents up to the test limit of 8 knots--over 4 times faster than many conventional skimmers.

Stage II efforts consisted principally of (a) designing and building a full scale (but 2-ft width) ZRV Belt and Wringer/Drive Mock-Up, (b) testing the mock-up in currents and choppy waves and (c) model testing the proposed skimmer hull configuration. Results of these tasks along with mathematical and experimental analyses have been used to design the prototype ZRV Skimmer.

The first chapter discusses the proposed prototype design--the end product of this second stage effort for the USCG. Subsequent chapters treat the elements of the program conducted to specify the prototype design and project its performance.

II. ZRV PROTOTYPE DESIGN AND PERFORMANCE

Introduction

The ZRV Prototype Skimmer Design summarized herein culminates over two years of concept development work conducted under contract to the U.S. Coast Guard (USCG) by Shell Development Company. The USCG program goal is to develop techniques to effectively recover spilled oil in 4 to 10 knot currents. The ZRV belt skimming concept has been shown by test to be capable of meeting that goal.

The detailed design and specifications were prepared under subcontract by Alan C. McClure Associates, Naval Architects and Engineers. Projected performance data was obtained from quantitative tests of a full-scale (in profile) mock-up of the concept. The projected prototype design and confirming test results are the end product of the second stage of the USCG's three stage program. The final stage concerns prototype fabrication and testing.

Design Description

The ZRV Skimmer is a 41-foot-long air-transportable aluminum catamaran vessel used to recover spilled oil in bays, harbors, estuaries, and coastal rivers and waters. Figure 2 is an artist's concept of the prototype, capable of recovering up to 600 gpm of a wide range of oils at a nominal operating speed of 6 knots. Principal dimensions and specifications are found in Table 1. For air transportability the skimmer is built in three sections: a port and a starboard catamaran hull, and a center skimming equipment section. Each hull, shown in Figure 3, has a 150 hp diesel propulsion unit, steering gear, and a temporary oil/water storage tank. The center section, shown in Figure 4, spans the catamaran hulls. It has an identical power unit to drive twin sorbent belts, transfer pumps, and associated equipment. The three sections are separated for air transport then assembled for use at the port nearest the spill. Special equipment for lifting, transporting, and aligning the sections is included with the prototype skimmer design.

Sorbent Belt Design and Operation

The skimmer uses twin sorbent belts, each 3-1/2 feet wide, to recover spilled oil under near-zero-relative-velocity (±1 knot) conditions. The composite construction of the belts, shown in Figure 5, permits recovery of oils ranging in viscosity from 2 to 2,000 centistokes. The outer sheath

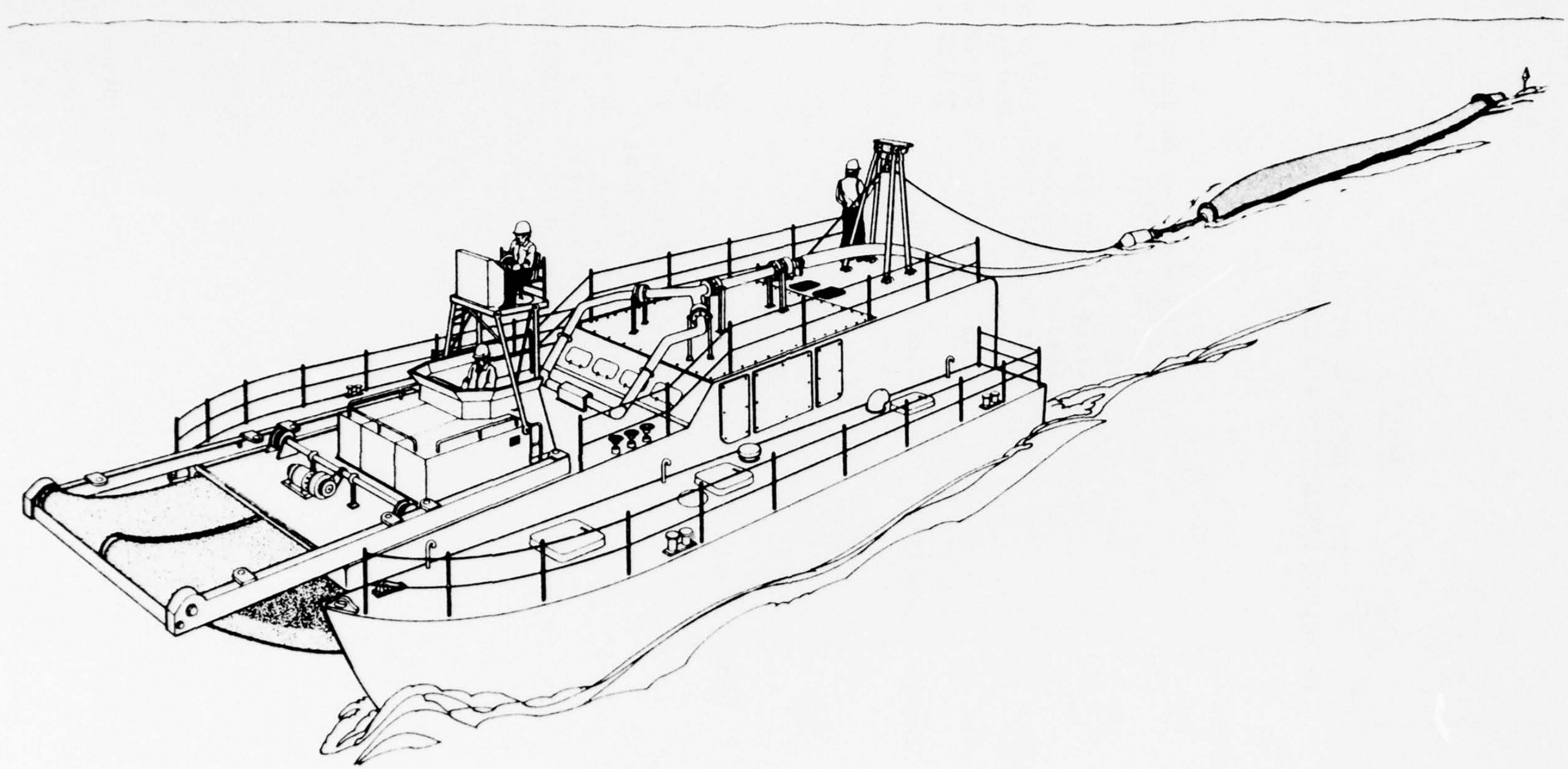

Figure 2. Artist's Concept of Prototype ZRV Skimmer

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TABLE 1

ZRV SKIMMER PROTOTYPE
PRINCIPAL DIMENSIONS AND SPECIFICATIONS

Assembled Skimmer

Length Overall	41' (Bow Roller Retracted)		
	49' (Bow Roller Extended)		
Beam	18'		
Displacement	Light 45,000 lbs		
	Loaded 51,000 lbs		
Propulsion Engines	Twin Diesels, each	150 HP	continuous
		210 HP	intermittent
Skimming Equipment	Single Diesel	150 HP	continuous
Power Unit		210 HP	intermittent
Recovered Oil Storage Capability	2,000 gallons		
Crew Required	3 - 1 Helmsman, 2 Seamen		

Center Section

Length	40'
Beam	9' 0"
Height (without transport skid)	6' 3"
Height (rigged for transport)	8' 5"
Weight	25,000 lbs

Pontoons

Length	40'
Beam	4' 6"
Height (without transport skid)	7' 6"
Height (rigged for transport)	8' 5"
Weight (each)	9,500 lbs

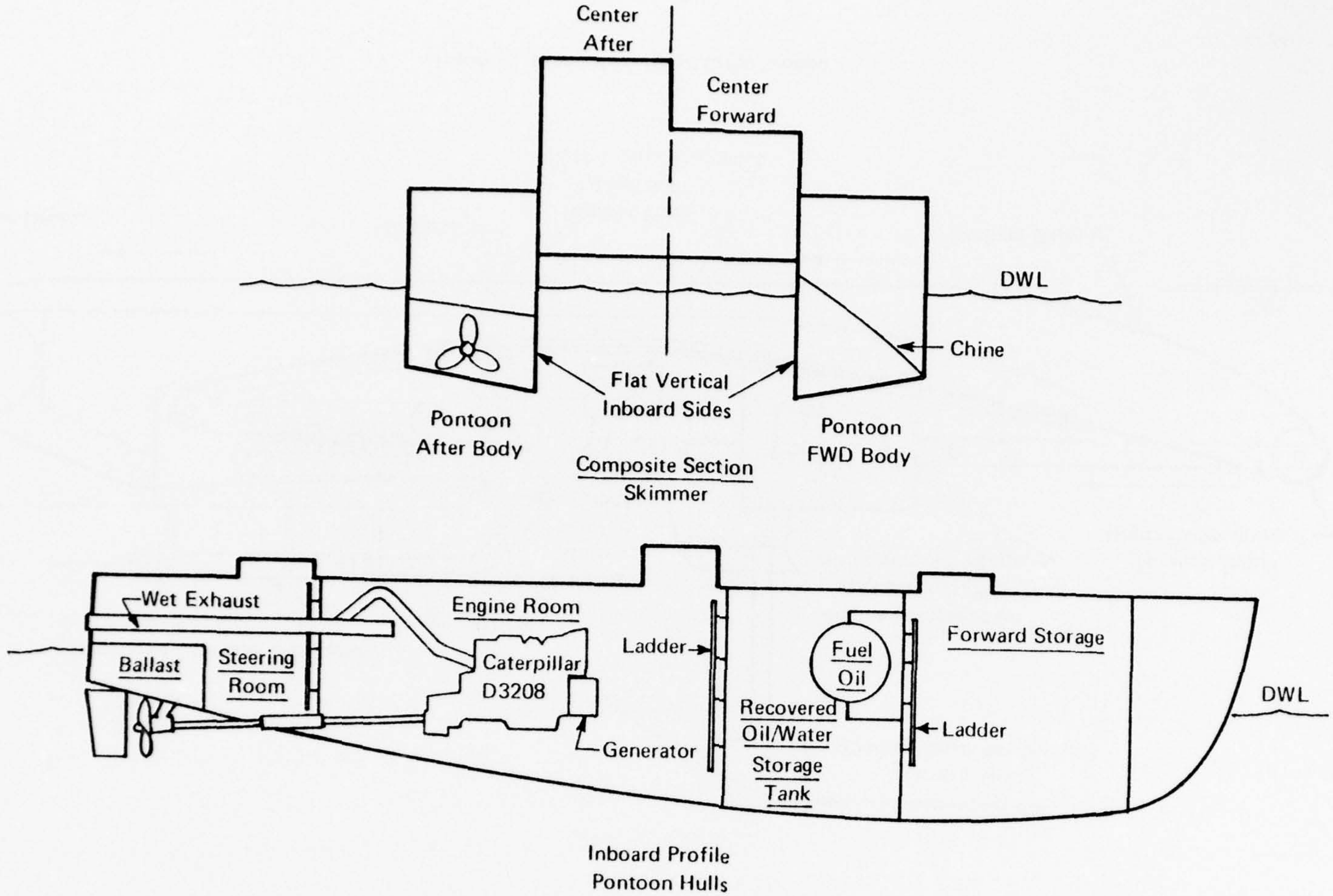

Figure 3. Pontoon Hulls

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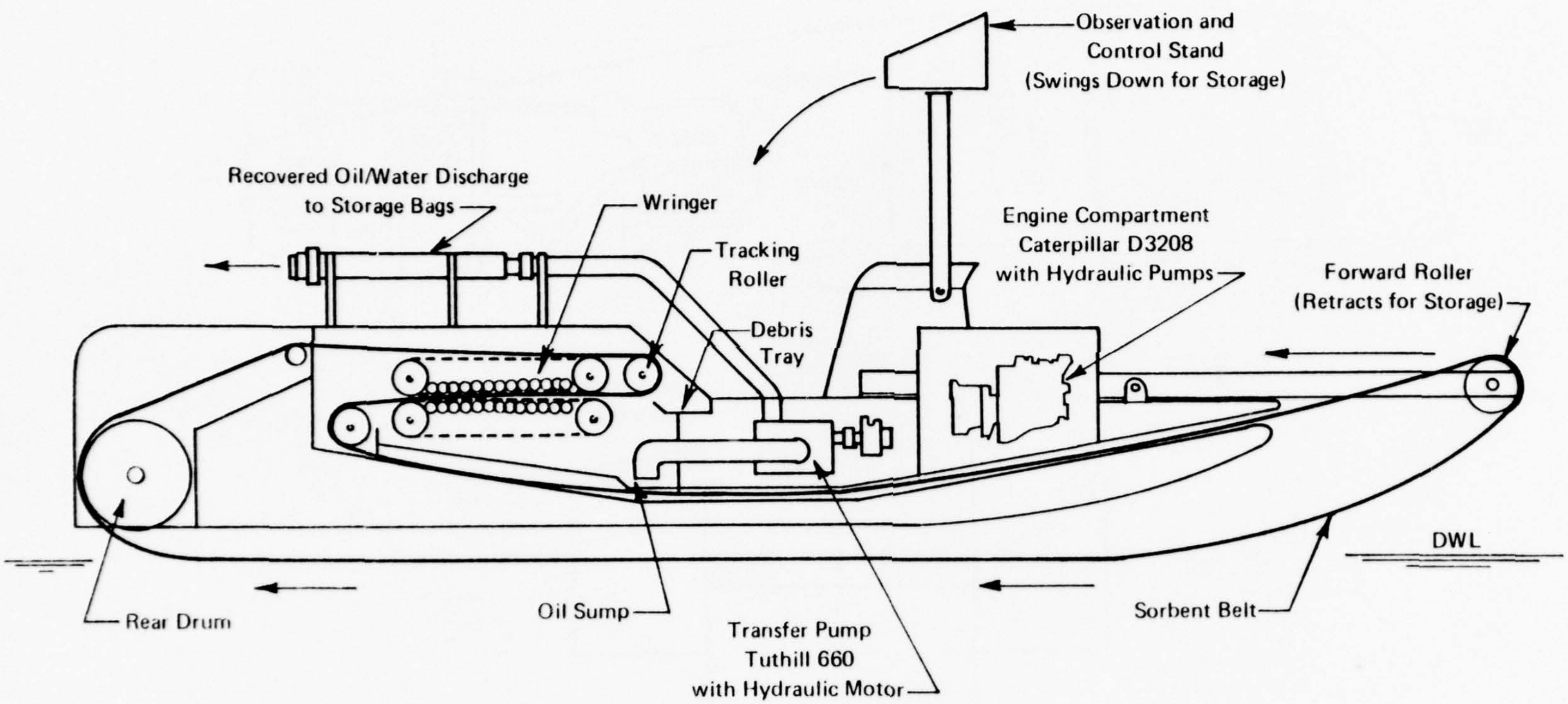

Figure 4. Inboard Profile – Cross Section

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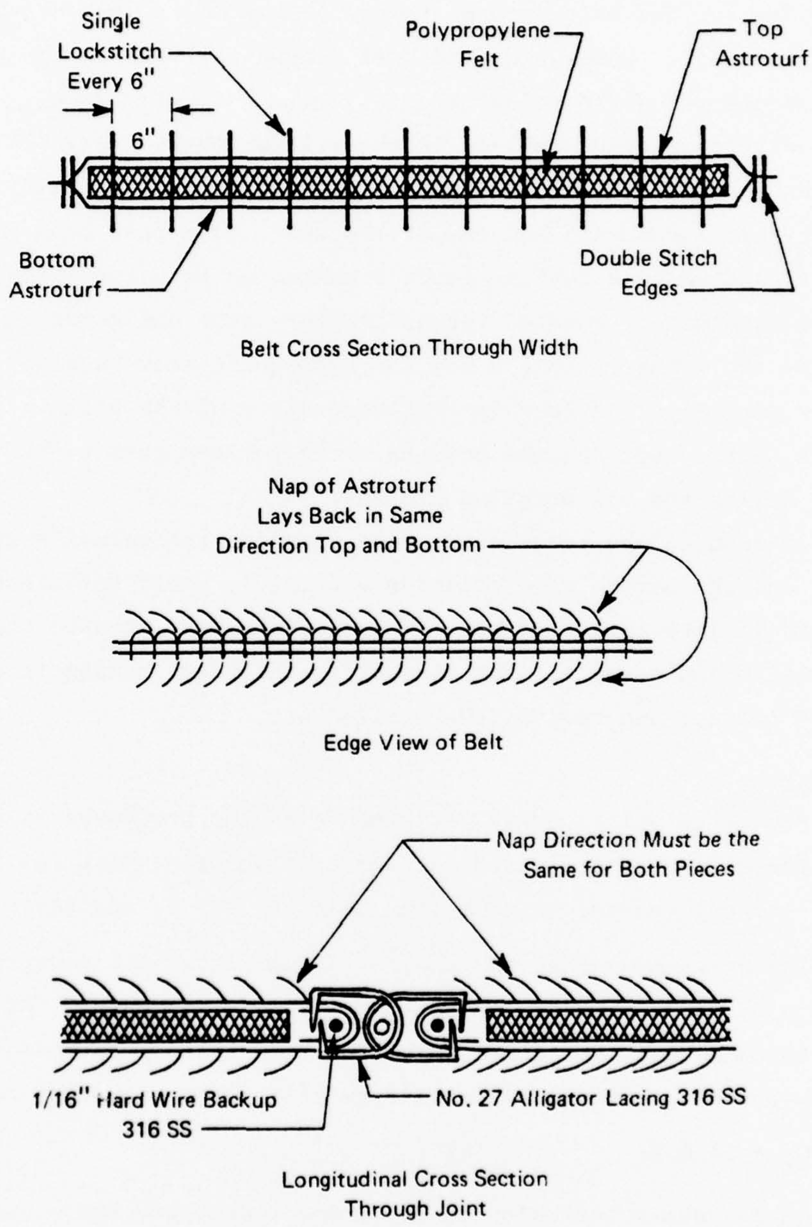

Figure 5. ZRV Belt Construction – Schematic

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of Astroturf (which adsorbs viscous oils) makes the belt strong and protects the inner layer of polypropylene felt (which absorbs light oils).

Each sorbent belt follows a continuous path through the recovery system, Figure 4. The belt path of travel allows sufficient contact time for sorbing spilled oil. Some water and most debris fall off as the belts are withdrawn around the stern roller while viscous oils and clinging debris are removed by wipers on guide rollers in the wringer entry area. In addition to driving the belts, the wringer (Figure 6) forces remaining fluid (except for a residual fraction) downward and out of the belt. The belt path is designed so that the oil-wetted belt surface faces downward as it passes through a wringer to ease oil expulsion. Powered forward rollers pull and guide the belts forward from the wringers to the bow for subsequent (low-tension) laydown on the water's surface. The loosely-tensioned state of the belt, in contact with the water's surface between the bow and stern rollers, permits it to conform with waves during the oil sorption process.

By running the belts at a speed matching the relative speed between the vessel and the water (zero relative velocity), shear turbulence is avoided at the belt/oil interface. At non-ZRV conditions, say greater than 1 knot, such turbulence can cause oil entrainment in the water making it difficult for the belt to contact and recover the spilled oil.

Oil Recovery

Projected oil recovery performance of the prototype is summarized in Table 2. These figures are based on quantitative tests of a full-scale* mock-up of the oil recovery system (see Chapters IV, V, and VI).

The data shows that the projected calm water oil recovery rate, Q_R, for the twin belts is directly proportional to belt speed, V, (at ZRV) and oil encounter thickness, t, for all oils tested. In fact at thicknesses $t < 5$mm the recovery rate is approximately 95% of the encounter rate, or

$$Q_R = 14.6\ Vt \qquad (\pm 5\%) \qquad \text{(Eq. 1)}$$

for $V < 8$ knots, where the units of Q, V, and t are gpm, knots and millimeters respectively.

*The mock-up had one two-foot-wide belt rather than two 3-1/2-foot belts.

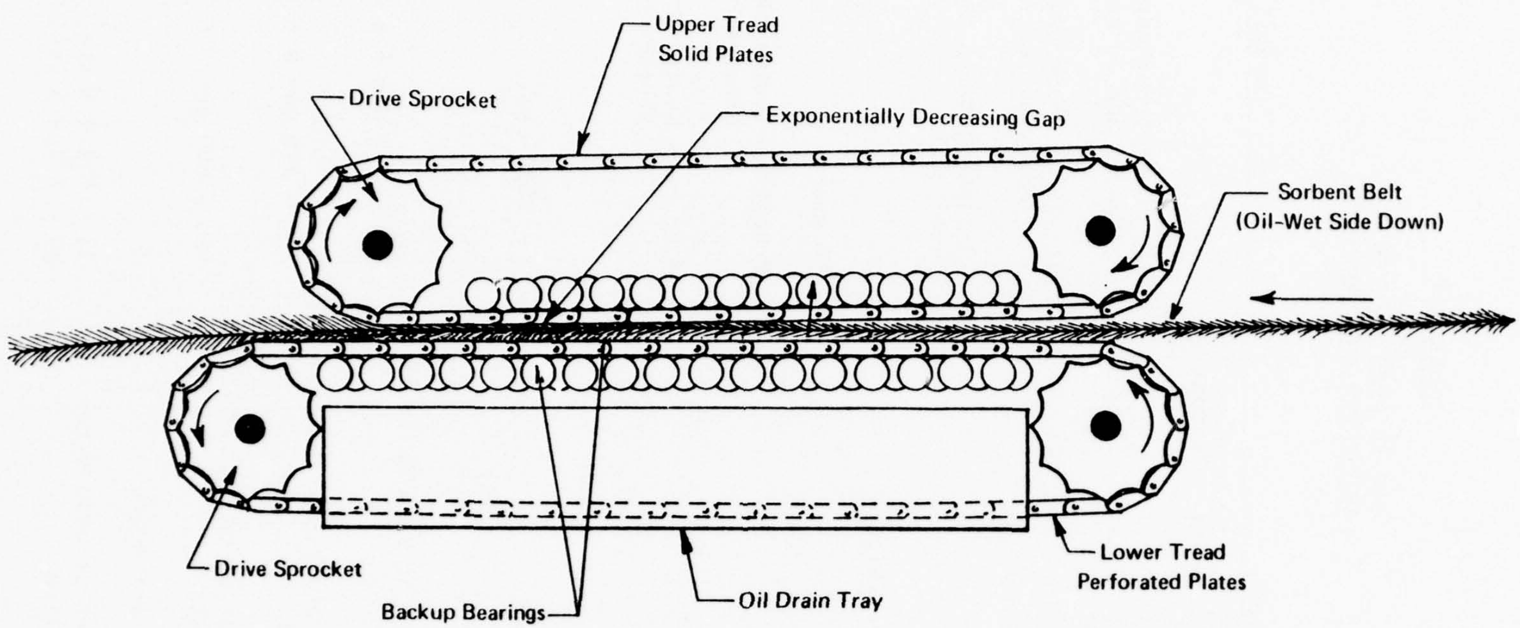

Figure 6. Wringer Profile

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TABLE 2

ZRV SKIMMER PROTOTYPE
PROJECTED PERFORMANCE

Condition	Capability
1. Seagoing Ability - Waves - Current	
a) Survival	a) 10 knot current with 4-foot waves and 20 knot winds
	b) 6-foot wave height with 40-knot wind for one week
b) Skimming	10 knots current with 2-foot confused seas
2. Speed and Maneuverability	
a) Transit	10 knots
b) Skimming	8 knots - Towing 14,000 gal. Storage bag
	6 knots - Towing 95,000 gal. Storage bag
3. Oil Recovery	
a) Viscosity Range	2 - 2000 cs.[a]
b) Recovery Rates	
i) Current or calm water 3mm slick	278 - 315 gpm @ 6 kts
ii) Two-foot irregular waves 3mm slick	236 - 270 gpm @ 6 kts
iii) Current or calm water 10mm slick	500 - 600 gpm @ 6 kts
c) Recovery Efficiencies	
i) Current or calm water 3mm slick	35 - 45% @ 6 kts, 2-30 cp oils 60 - 75% @ 6 kts, 100-1200 cp oils

a. The skimmer may pick up oils with higher viscosities but no test data is available to confirm this. Actual test oil viscosities ranged from 4 to 1100 cs but this can be safely extrapolated to 2 - 2000 cs.

TABLE 2 (Cont'd)

ii)	Two-foot irregular waves 3mm slick	25-35% @ 6 kts, 2-30 cp oils 40-55% @ 6 kts, 100-1200 cp oils
iii)	Current or calm water 10mm slick	80-95% @ 6 kts, 2-1200 cs oils
d)	Throughput Efficiencies	
i)	Current or calm water 3mm slick	90-100% @ 6 kts
ii)	Two-foot irregular waves 3mm slick	90-100% @ 6 kts
4.	Belt Life	Over 200 hrs

The maximum recovery rate, $Q_{R(MAX)}$, depends on the belt sorbing capacity, the sorption time, and the encountered oil viscosity. Based on test data we expect $Q_{R(MAX)}$ to be 600 gpm for light distillates and to reduce to 525 gpm for more viscous residual oils. These maxima can be expected for slick thicknesses, t, greater than 8mm. Corresponding through-put efficiencies (oil encountered vs. oil recovered x 100%) under conditions of Equation 1 are from 90 to 100% for all oil viscosities tested.

Generally speaking, the projected oil recovery performance is not altered by ±1 knot deviations from ZRV conditions. Although moderate (<2 ft) inshore waves do not appreciably affect the oil recovery performance, confused two-foot waves lower the throughput efficiencies and hence oil recovery rates by about 15%.

Recovery efficiency (volume of oil recovered vs. volume of oil + water recovered x 100%) of the ZRV improves with increasing skimming speeds. At higher speeds increased centrifugal force at the rear drum throws off loosely held water which would be retained and collected at lower speeds. Calm water recovery efficiencies for 3mm oil slicks vary from 40% for light distillates to 75% with heavier residual oils. Maximum recovery efficiencies of 80 to 90% are achieved with thick (> 5 mm) slicks at high (6 - 10 knot) speeds.

Although oil recovery rates are hardly affected by waves (up to 2 ft) corresponding recovery efficiencies can decrease by as much as 50%. However this number is based on mock-up tests using an unprotected belt where waves washed over the sides. A less dramatic decrease in recovery efficiency in waves is expected for the prototype since the pontoons protect the belt sides. Some decrease will occur, however, because wave action causes water to fill the remaining void volume or attach to the surface of the belt after oil sorption occurs.

Oil Transfer and Storage

Recovered oil and the water collected with it drains to a sump amidships after falling from the wringer. Two 600 gpm rotary-type positive displacement pumps (Tuthill Moded 660) pick up the collected oil and send it to onboard or external temporary storage. These pumps were chosen for their self-priming and debris-handling characteristics as well as their ability to pump all types of oils. They are relatively compact, lightweight and inexpensive

compared to other positive displacement pumps studied. The pumps are hydraulically powered for variable speed so that the transfer rate can match the recovery rate.

For small spills or final clean-up operations in larger spills, oil may be pumped directly into a 1,000 gallon storage tank located in each hull. For spills exceeding about 500 gallons, external storage must be used. This could be a barge or tank onshore, for example, if the skimmer were moored in a river. Underway in a harbor or bay, towable oil storage bags could be used. These are commercially available from several rubber companies. A 95,000 gallon bag can be towed at 6 knots and would take 2-1/2 hours to fill at 600 gpm. Both transfer pumps are manifolded to an on-deck discharge line for external storage, as shown in Figure 2.

Vessel Power and Controls

Three identical turbocharged diesel engines (Caterpillar Model D-3208) power the skimmer. An engine in each pontoon hull drives a fixed-pitch propeller enabling the skimmer to operate at speeds up to 10 knots. These engines also drive generators to provide electrical power for auxilliary functions. The center-section engine drives several hydraulic pumps providing power for the wringer, forward roller, and transfer pumps. Having its own power source, the center section operates independently of the rest of the vessel.

The three engines and the functions they power are controlled from a pilot house on deck. Controls are manual except for the belt speed, which may be automatically or manually controlled. Main controls are duplicated in an elevated control stand. The stand, which swings down for storage, provides an eye elevation of about 17 feet above waterline to give a better view of approaching oil slicks. Underway, a helmsman can steer from the elevated station while a crewman monitors oil recovery from the pilot house. The third crew member can monitor oil transfer operations.

Deployment

For fast response to an oil spill emergency the ZRV Skimmer can be airlifted to the port nearest the spill, trucked to the dock, assembled, and launched. From there it can proceed under its own power to the spill site. Two C-130 cargo planes are required for the airlift. The port and starboard pontoons fit in one aircraft and the center section in another. The three

sections are stored on steel skids with heavy duty rollers and jacks for handling. At the dock pre-attached cable slings facilitate assembly. Tapered pins guide the pieces together and angle brackets are used to join them into one vessel. After making several piping and electrical connections the skimmer can be lifted off its skids into the water. If a large crane is not available it may be ramp launched.

Normal modes of operation are shown in Figure 7. The skimmer may be moored in rivers and currents with separate narrow-angled diversionary booms directing oil to the sorbent belts. Recovered oil may be pumped into a barge moored alongside or into a temporary storage tank on the bank. In open waters the skimmer can proceed under its own power, pulling a towable storage bag behind. Experience indicates that skimming in following seas, that is, "with" the waves, is preferred because of resulting reductions in turbulence.

Mechanical Reliability

The conventional components of the prototype skimmer have been designed according to accepted engineering practices to provide good reliability. Several redundancies are built into the design. For example, there are two vessel propulsion means and two transfer pumps. Unconventional components -- in particular the sorbent belts and wringers -- have been successfully tested in a full-scale mock-up. No major reliability problems are expected with the skimmer.

The sorbent belts are very durable. They should have an operating life of well over 200 hours, based on belt life tests and mock-up tests. In fact, the same belt was used during the entire mock-up test program. The chances of damage by debris are small since the belts lay gently over debris, with no relative velocity to cause tearing or cutting. Heavy debris is simply left behind as the belt is withdrawn and light debris is scraped off prior to wringing. Astroturf is wear-resistant and does not propagate cuts and tears. The most likely places that damage will occur is at the steel splices. Damage there can be repaired easily by trimming the ends of the belt and installing new lacing.

The component with the most questionable reliability is the wringer. It is the most complex and unconventional piece of machinery in the skimmer. However, a full-scale mock-up has been successfully tested and evaluated. Design changes based on information from the mock-up tests should yield

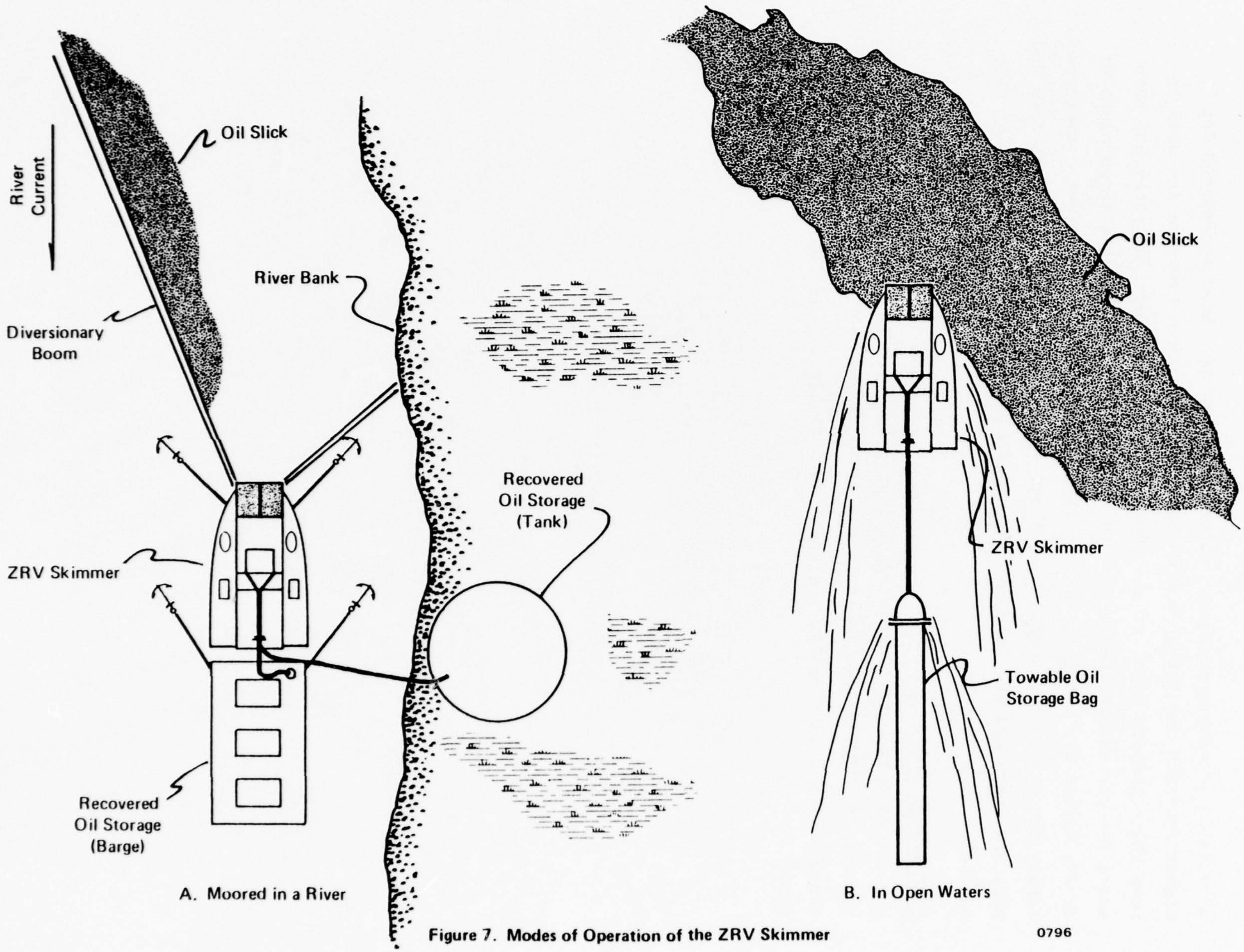

Figure 7. Modes of Operation of the ZRV Skimmer

a reliable prototype wringer. Conveyor plates have been redesigned for higher strength and better motion control. Hydraulic take-ups are used to keep the conveyors tight at all times. Also, a lubrication system has been added for the support bearings. In the unlikely event that a large piece of debris enters the wringer, the gap will open automatically to avoid overpressuring the conveyor plates. Should one section of the wringer break down the port and starboard sections can be uncoupled and skimming resumed using only one belt.

USCG Design Goals

As a result of the Stage 2 test program, technical information on nine of the USCG design goals is available, shown in Table 3. Appendix A contains the entire design goal list as modified by the USCG in January 22, 1976.

TABLE 3

USCG DESIGN GOALS ADDRESSED IN STAGE II

Design Parameter	Goal and/or Range of Values[a]	Prototype Specifications and Projections Based on Stage II Results
A. Operational Environment	Currents up to 10 knots with optimal recovery at 6-7 knots; waves up to 2-foot confused seas with 20 knot winds.	Full scale mock-up tests showed effective recovery at 6 knots in 2-foot confused seas.[b]
B. Oil Type	Recover a complete range of oils including: a) distillate fuel oils b) residual fuel oils c) crude oils Optimal recovery range; 10cs to 500cs	Effective oil recovery was achieved using: a) No. 2 Fuel Oil-3cs b) Sunvis 7 Lube Oil-30cs c) Medium Blend Residual[c] Oil-130cs d) Heavy Blend Residual[c] Oil-700cs e) Sunvis 1650 Lube Oil-1100cs
C. Oil Control	The system shall be capable of controlling oil so that it can be recovered.	The ZRV prototype is a mobile high speed oil recovery craft. Control and containment of oil can best be accomplished by mechanical booms and chemical surface active agents. These are necessarily low-speed methods and as such are not compatible to a high speed vessel.
D. Oil Recovery	Should be characterized by: a) throughput efficiency $\geq$ 95% b) recovery efficiency $\geq$ 75% c) recovery rate up to and including 1000 gpm	a) Throughput efficiency 90-100% b) Recovery efficiency 25-95% c) Recovery rates up to 600 gpm Please refer to Table 2 for additional details.
E. Debris Handling & Protection	Shall be able to handle a moderate amount of debris	Debris is no problem by design. The sorbent belts gently pass over most debris. A wiper and debris tray remove and collect any debris that clings to the belts in spite of the centrifugal forces encountered during withdrawal.

TABLE 3 (cont'd)

Design Parameter	Goal and/or Range of Values[a]	Prototype Specifications and Projections Based on Stage II Results
F. Mode of Operation	Moored, towed and self-propelled.	The prototype has standard marine fittings for mooring and towing. Twin diesels provide power for cruising at 10 knots.
G. Transport from Central Storage to Nearest Port	One C-141 or two C-130's (two modules 39' x 9' x 7'10" LWH with max. weight of 25,000 lbs each)	The prototype design meets these weight and dimensional restrictions.
H. Pump and Transfer Function	Pump up to 1000 gpm without emulsfying the oil.	Two Tuthill Model 660 positive displacement pumps on board have a total capacity of 1200 gpm. These pumps were chosen on the basis of a Shell study which compared the performance of three positive-displacement pumps under similar test conditions. Debris handling, suction lift, and emulsification characteristics as well as size and weight were considered.
I. Temporary Storage	Temporarily store 2000 gallons aboard and 500 long tons by external means.	Each pontoon hull has a 1000 gallon storage tank. A 6-inch discharge line is provided to transfer oil to larger external containers such as barges, pillow tanks and towable bags. These containers are not provided with the skimmer.

a) Design goals as modified January 22, 1976. See Appendix A.
b) Wave tank restraints limited testing to 6 knots maximum.
c) Blend of LVI (Low Viscosity Index) Flux (a grade of asphalt), No. 2 Fuel Oil, and refinery cutting stocks.

III. MOCK-UP DESIGN

Introduction

The USCG fast current oil recovery equipment research and development program is structured into three parts: First, a small-scale concept verification stage; second, a larger scale equipment testing stage and finally a prototype fabrication and test stage. In Stage I[1] the ZRV concept was proven by coupon tests using belt-configuration and wringer simulators. The results were adequate to prove the concept but insufficient to verify full-scale prototype performance. Clearly, the next step (Stage II) was to design, construct and test a prototype-like belt and wringer/drive mechanism. The belt sorption properties could not be reliably modeled at small scale so the belt length and path-of-travel was designed to be full-scale. Since (within limits) oil collection performance is linearly related to belt width, a narrower-than-prototype belt was used.

The Stage II approach was to design and build a ZRV belt and wringer/drive "mock-up" that had full-scale properties except that, for economy, one 2-foot-wide belt was used rather than two 3-1/2-foot-wide belts as in the prototype. Further, the prototype vessel--a costly part of any advancing skimmer--would not be needed: (1) the mock-up could be suspended above the water during oil recovery tests and (2) the vessel design could be small-scale modeled and tested in waves and currents (or speeds) as most vessel designs are tested.

This approach is valid because in prototype scale the vessel responds to larger waves (>2 ft), while the belt must conform to smaller waves (<2 ft and not affecting the vessel). With this reasoning the vessel response could be obtained separately and at a reduced scale from the oil collection response. This implies that the catamaran vessel must be designed to avoid turbulence in the belt operation area between hulls: Otherwise vessel-belt interactions would occur, violating the modeling scheme.

Basic Configuration

The basic layout of a prototype skimmer was outlined in Stage I[1]. The mock-up for Stage II had to conform to prototype geometry, except for width. Components not found in the prototype but required for mock-up tests--wheels, sample collection trays and tanks--had to fit into remaining

space after the prototype geometry was attained. Specific design goals for the mock-up were: resemblance to prototype, simple operation, easy modification, rapid construction and low cost. While oil recovery performance was not sacrificed, weight and operating life of mechanical parts were sacrificed in some cases to meet these goals.

This mock-up, shown in Figures 8 and 9, was designed to be towed by truck over a narrow test canal for the Houston tests. With wheels removed and special mounting brackets added it could be suspended between two moving bridges for the OHMSETT tests. The main framework of the mock-up was a box of structural steel built from two 50-foot prefabricated steel joists. This open framework enabled components to be easily mounted within, both in the initial construction and in later modifications. Mechanical equipment could be seen and photographed well through this framework. Table 4 lists the components shown in Figure 9 and describes their functions.

Wringer Design

One of the major areas of concentration during the design stage was in the wringer design. The basic concept of using paired conveyors separated by an exponentially decreasing gap was good. However, initial investigations showed that high speeds and loads inherent in the wringing process would cause considerable design problems. Chain belting originally intended for the conveyors could not withstand the loads or speeds required. In addition rough calculations showed that the 15-foot wringer would require on the order of 500 horsepower to overcome frictional losses.

The mock-up wringer, in its final form, Figure 10, successfully overcame the speed, load, and power problems. Rather than using chain belting, the conveyors were made of 4-inch by 24-inch hardened steel plates welded to a single 2-inch double-pitch conveyor chain. Essentially these were conventional table-top conveyors. But by supporting the steel plates with heavy-duty cam follower bearings and keeping the chain taut and constrained by guides, these conveyors could be operated at high speeds and still resist the heavy wringing loads applied. While running the conveyor chain at high speeds under high tension loads would shorten its duty life, chain wear was not considered to be a significant problem because of the relatively short mock-up wringer use.

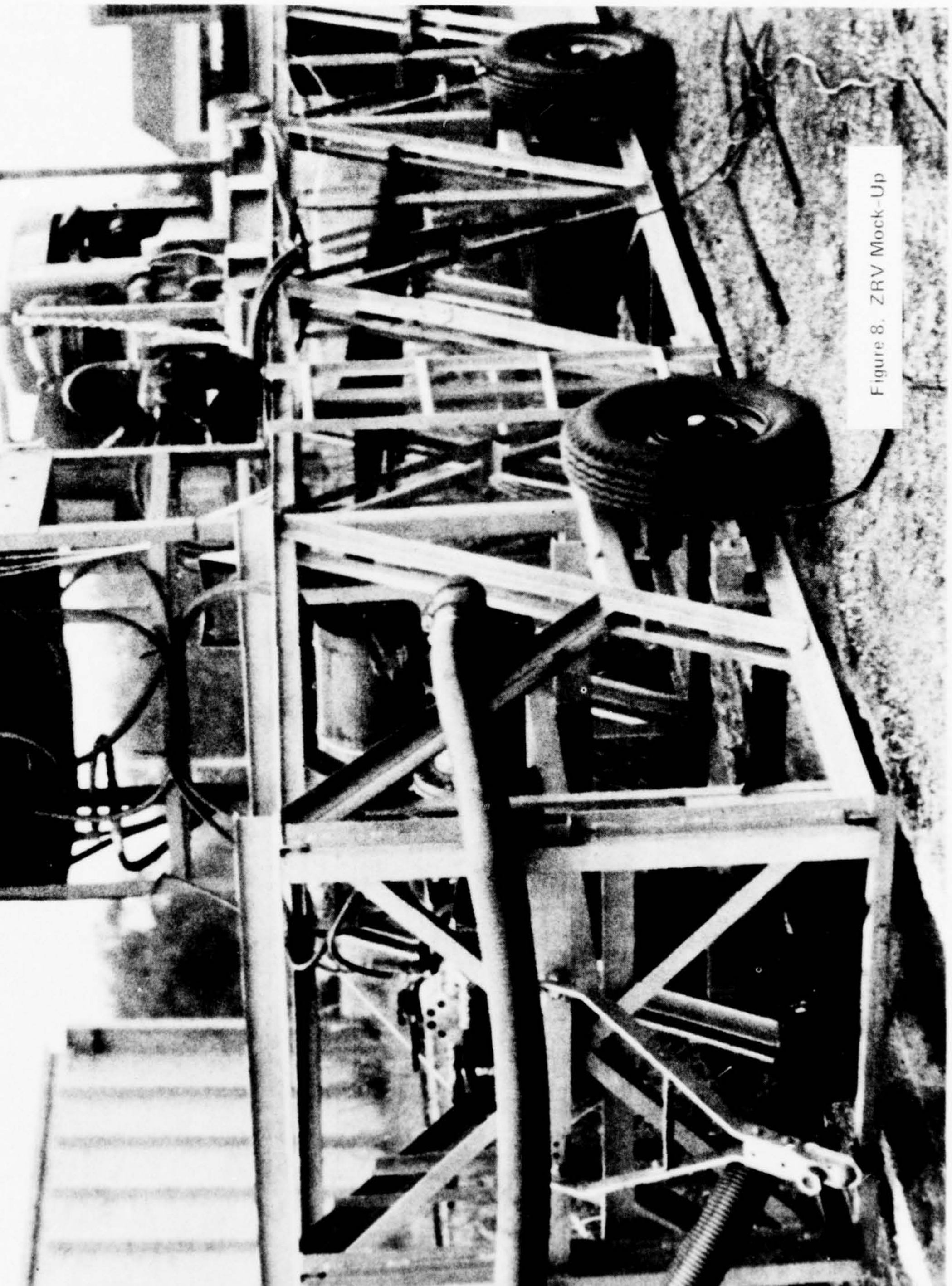

Figure 8. ZRV Mock-Up

Not to Scale

Refer to Table 4 for
Description of Components

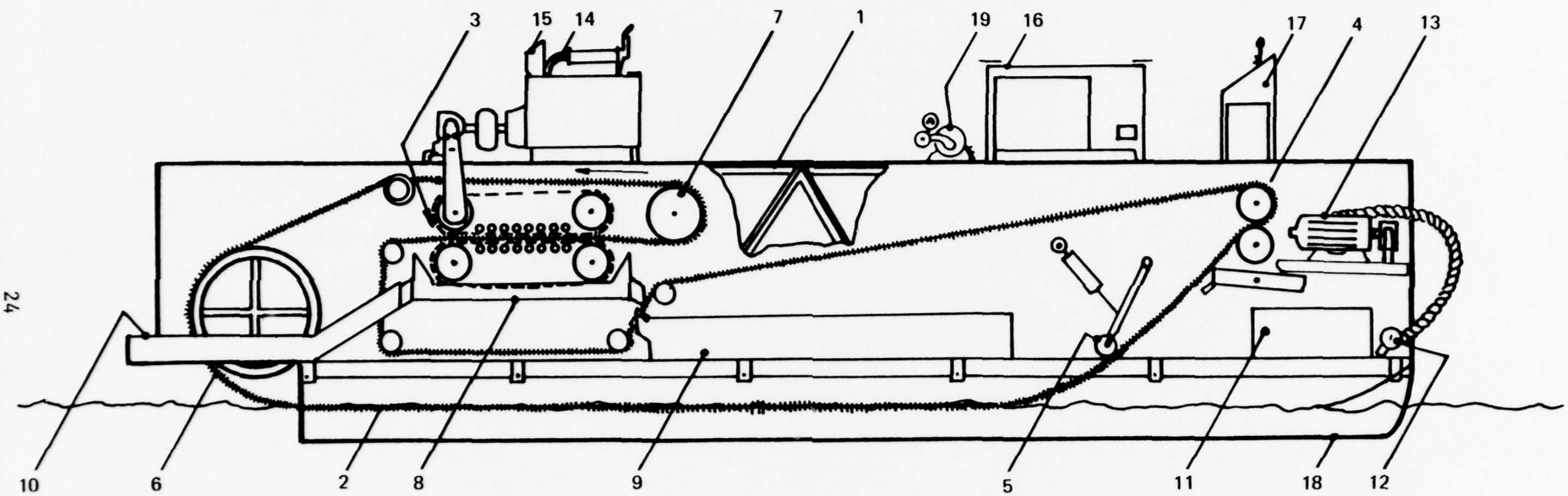

Figure 9. Mock-Up Diagram

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TABLE 4

MOCK-UP COMPONENTS
(Refer to Figure 13)

	Component	Description	Function
1.	Main Frame	50 x 4.5 x 4.5 LWH in feet; structural steel framework	Provides support for all other components.
2.	Sorbent Belt	2-foot-wide composite belt of Astroturf and polypropylene felt,120 feet long	Sorbs and recovers oil floating on water for subsequent recovery.
3.	Wringer	High-speed opposed-conveyor pair wringer. Conveyors were made of steel plates welded to carrier chain supported by needle roller bearings.	Wrings recovered oil from the sorbent belt. It also drives the belt.
4.	Front Rollers	Hydraulically powered, 12-inch diam. conveyor rollers spaced 3/8 to 1/2 inch apart.	Pulls sorbent belt to front of mock-up from wringer.
5.	Belt Tension Roller	Conventional 6-inch diameter roller mounted on a pneumatically operated arm in forward part of mock-up.	Provides proper belt tension. Later this was replaced with a spring-loaded sled device for OHMSETT tests in waves.
6.	Rear Drum	Four-foot diameter roller drum, vertically adjustable.	Provides proper belt withdrawal geometry.
7.	Guide Roller	Crowned 20-inch diameter conveyor roller, horizontally adjustable.	Takes up slack as belt stretches; also guides belt into wringer.
8.	Tilt Pan	Pivoting, pneumatically-operated sheet metal tray with four spring-loaded flow-control doors.	Controls flow of recovered oil; tilts forward to collect sample, and back otherwise.

TABLE 4 (cont'd)

	Component	Description	Function
9.	Main Sample Collection Pan	Baffled sheet metal pan 16 x 3.5 x 1 LWH in feet.	Collects recovered oil sample from wringer.
10.	Slop Oil Chutes	Two sloping sheet metal chutes 8 x 1/2 x 1/2 LWH in feet.	Conduct recovered oil from wringer to test canal when not sampling.
11.	Forward Sample Collection Pans	Two sheet metal pans 3 x 1.5 x 1.3 LWH in feet.	Collect oil squeezed from belt by front rollers (oil missed by wringer).
12.	Oil Distribution	9-nozzle manifold with 4-inch inlet	Spreads oil on canal during tests for subsequent recovery by sorbent belt. This was later abandoned.
13.	Oil Distribution Pump	500 GPM hydraulically powered gear pump with tachometer, Roper Model 4793NBFRV	Pump and meter oil from supply tank (on tow vehicle) to distribution nozzle. This was later abandoned.
14.	Wringer Engine and Drive Train	Ford 330 V-8 engine coupled to a modified Corvette differential by a Twin Disc Model 17.5 HCM fluid coupling.	Powers the wringer.
15.	Wringer Instrument Box	Plug-in box containing wringer speed tachometer, belt/vehicle differential speed meter and electronic stopwatch.	Provides speed information to wringer operator; also records sampling time.
16.	Hydraulic Power Package	Skid-mounted hydraulic power package powered by a 70 HP, 4-cycle Ford diesel engine.	Powers the front rollers and the oil distribution pump.
17.	Hydraulic Control Panel	Standing control panel with pump speed meter, pressure gauges, flow control valves & tilt pan actuating valve.	Controls front roller, oil distribution pump, and tilt pan position (for sampling).

TABLE 4 (cont'd)

	Component	Description	Function
18.	Belt Guide Fins	Sheet metal guides hung vertically below sides of the main frame, piercing the water's surface.	Guide belt laterally on the water. (Later shortened, then replaced)
19.	Nitrogen Bottle	Standard high-pressure nitrogen bottle with regulator.	Provides pneumatic pressure to actuate tilt pan and belt tension roller.

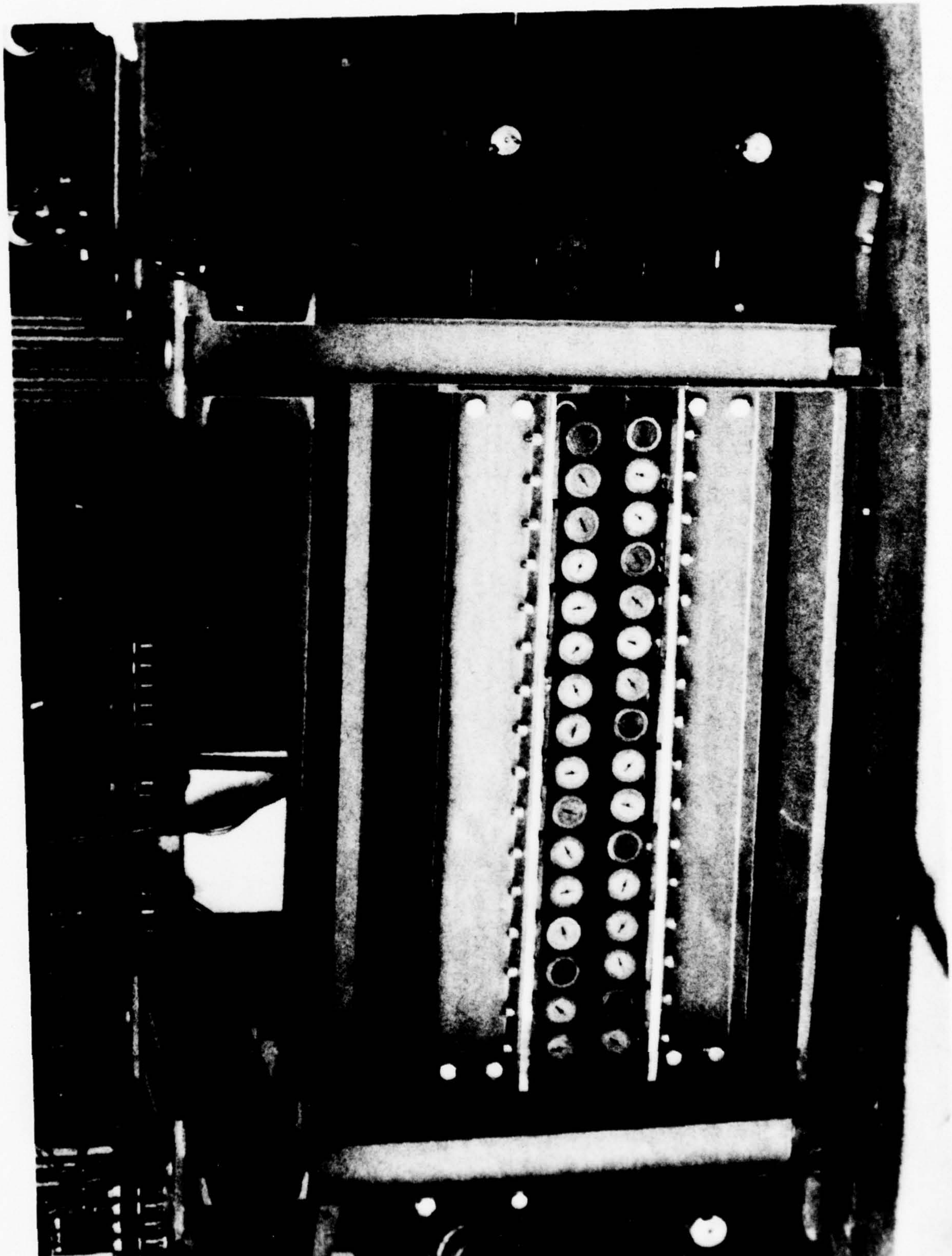

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Figure 10. Mock-Up Wringer

Mathematical analyses showed that frictional horsepower losses in the wringer were directly proportional to wringer length and to the average compressive load. To reduce these losses, and consequently the wringer drive power, its length was shortened from 15 feet to 5 feet. Since this would increase the wringer squeezing rate threefold, tests were conducted using the wringer simulator developed in Stage I to confirm that belt damage was unlikely. Also, to further reduce power requirements, GAF EX 745 felt was substituted in the composite belt in place of the original EX 1017 felt. EX 745 has almost the same oil absorption capacity as EX 1017 but can be compressed with only one-third the force required for EX 1017. This was a significant change, since compression tests had shown that most of the load on the wringer was caused by compression of the inner felt layer.

Wringer Design Details

Wringing was accomplished in the mock-up by forcing the sorbent belt through a fixed gap between the wringer conveyors rather than applying a specific pressure to the belt. Support bearings behind the conveyor plates were shimmed so that the wringer gap decreased exponentially from wringer entrance to exit. The high normal loads generated by wringing provided more than adequate traction to drive, or propel, the belt without slipping.

The wringing loads were designed to be internally resisted by the wringer and not transmitted to the mock-up framework. The lower conveyor was welded to the supporting framework. The upper conveyor--identical but placed upside-down with respect to the lower unit--was supported by four vertical 2-inch threaded rods extending from the lower conveyor. Turning the rods moved the upper conveyor vertically so that the gap between the conveyors could be set. Compressive wringing loads tending to separate the conveyors were entirely balanced by tensile loads in the threaded rods. This design facilitated mock-up construction since no special reinforcements were required in the main frame to handle wringing loads.

In designing the mock-up wringer every effort was made to use only standard, off-the-shelf components and welded fabrication for expediency and economy. Components which required machining or other expensive manufacturing processes were avoided where possible.

This design approach worked well in most cases. However, several problems surfaced. The lower conveyor plates, which had to be perforated for oil drainage, were made of thin 1/4-inch steel plate so that they could be sheared to size and economically perforated by punching. Thicker plates would have required expensive, time-consuming castings or machining. However, in order to withstand the bending stresses imposed by wringing loads the 1/4-inch plates had to be heat-treated. Unfortunately, many of the plates were too warped for use after heat-treatment and were scrapped. Because thin plates were used, a large number of support bearings were required to prevent serious deflection of the wringer plates and the resulting variation of squeezing gap across the width of the wringer.

A second problem was warpage, inherent in welded structures. This, coupled with the coarse tolerances maintained in structural steel, caused serious misalignment in the wringer framework. Such misalignment made it very difficult to establish the proper wringer gap geometry.

Finally, another problem, peculiar to the chosen chain and plate conveyor design, surfaced. During the initial performance tests of the mock-up at Houston, oil expelled from the sorbent belt was observed being re-absorbed near the wringer exit. The expelled oil concentrated particularly in the lower conveyor back-up area and flowed toward the exit of the wringer. As the wringer plates reached the exit they would separate while negotiating the turn, allowing oil to spray out and reattach to the belt. This reduced the wringer efficiency.

Because the thin wringer plates required many back-up rollers, little space was available to incorporate multiple wipers, or vertical dividers, to escort the expelled oil from the wringer location. This mock-up wringer problem was not totally overcome because little could be done from a practical standpoint without extensive changes. It was minimized principally by (1) carefully fitting transverse wipers between the cam follower bearings close to the wringer exit location, (2) installing a "pre-wiper" on the take-up roller just in front of the wringer entrance to remove some oil before the belt enters the wringer and (3) installing sample recovery pans at the forward drive rollers so that "secondary" wringing could occur there.

These problems for the most part were overcome without major modifications and the wringer worked satisfactorily.

Sorbent Belt Design

Another major problem studied during the mock-up design task was how to construct the sorbent belt. The belt materials--Astroturf and polypropylene felt--were selected in Stage I but no method of joining them into a durable belt had been analyzed. Methods considered were sewing, stapling, riveting, and adhesive bonding. After evaluating each method, sewing with longitudinal seams (only) was chosen as the best way.

The original belt concept was one strip of Astroturf backed by a single layer of felt. However, the felt surface not protected by the Astroturf was subject to damage by the belt handling machinery. A tough porous cover was needed to protect the belt and also help prevent stitches from pulling loose. Many types of backing were evaluated for toughness, porosity and compatibility with the other belt materials. The simplest solution was to use a second layer of Astroturf. Several different belt construction schemes, each belt having a layer of felt sandwiched between two layers of Astroturf, were cycled 60,000 times through a conventional washing machine-type wringer with excellent results (see Chapter IX). The design believed most practical was shown previously in Figure 5.

Belt Tracking

A third major problem studied in designing and constructing the mock-up was the tendancy of the moving belt to drift to one side or the other. A mathematical study done in Stage I indicated that there was no reason why the ZRV belt could not be tracked (i.e., aligned) with proper control mechanisms. However, very little was known about the control mechanisms that could track a wide, very pliable, loose-tensioned belt at high speeds. Conventional conveyor belts are relatively stiff. They are kept under much higher tension and are not usually run at speeds over 600 ft/min (6 knots). Relying on conventional conveyor technology, it was assumed that the belt could be guided with correctly aligned rollers. Another conventional technique employed was to crown the rollers--make rollers slightly larger in diameter in the center than at the ends. Belts have been found to center themselves naturally this way. The long belt span between the wringer

exit and the forward rollers was supported on a sheet metal trough, slightly wider than the belt with a 3-inch vertical lip on either side. Vertical sheet steel guides initially running the entire length of the mock-up were used to guide that part of the loosely-tensioned belt on the water. These 40-foot-long guides extended 2-4 inches below the water's surface.

During the initial shakedown of the mock-up in Houston, proper roller alignment was found to be essential to avoid belt jamming. Nearly all of the rollers had to be adjusted to center the belt dynamically. The rollers that had the most effect on controlling tracking were those where the belt made 180-degree turns: the rear drum, the guide roller just forward of the wringer and the forward rollers (see Figure 9). Other rollers had little effect on belt tracking. The crown in the rollers seemed to have no effect on belt tracking, presumably because the belt was too loosely-tensioned. The crown in the rear drum and forward rollers was removed after testing began with no ill effect. Flanges were added to the ends of several rollers to give them 1-1/2-inch high lips for the belt edge to drift against. These provided some control when the belt was moderately well-tracked. However, when one of the main rollers was badly misaligned the belt easily climbed over the flanges, wrinkling in the process.

In addition to maintaining correct roller alignment, the use of sidewalls to limit the side-to-side travel of the belt was found to be effective. Attempts at OHMSETT to run the belt on the water without guides failed. Above water, troughs with vertical sides like the one running from the wringer to the forward rollers worked well. The full length vertical belt guides piercing the water in the Houston tests tracked the belt well but created too much turbulence at speeds over 4 knots. These guides were eventually shortened as much as thought possible to extend from the rear drum to a location eight feet forward. This change reduced the turbulence and significantly improved the mock-up performance. When similar surface-piercing belt guides were added at OHMSETT, turbulence from the guides was seen for the first time to spray water on top of the belt. Undoubtedly this had happened at Houston but was not visable because of the nature of the test facility. New non-surface-piercing guides were subsequently added at OHMSETT which successfully tracked the belt onto the rear drum after the belt left the water. These short guides, just in front of the rear drum, were about one foot above the water's surface. They worked well even when confused waves pushed the belt laterally.

IV. MOCK-UP PERFORMANCE TESTS - PART A (HOUSTON)

Introduction

Part A of the principal confirming tests of the ZRV Mock-Up (containing a 2-foot wide but full-scale belt) took place at Shell's Gasmer Road Laboratory in Houston, Texas. The test tank was an 875-foot long concrete trough, or canal, 3 feet wide and 1 foot deep, filled to a depth of approximately 0.7 feet with fresh water.

Objectives of this series of test runs were to (1) de-bug the expected belt and wringer drive mock-up mechanical problems, (2) confirm procedures and apparatus for testing at high speeds--from 4 to 10 knots, (3) collect full-scale oil recovery performance data (in the absence of waves) needed to project prototype performance and (4) discover any belt durability and mechanical reliability problems that might require further design consideration. Objectives 1, 2 and 4 would be met through efforts to accomplish objective 3.

Test Apparatus and Facilities

The ZRV Mock-Up was fitted with trailer wheel assemblies such that it could be towed by a 1-1/2-ton truck down the 875 foot canal, the wheels of the mock-up and truck straddling the canal. Then at a given truck tow speed the belt speed could be matched, causing a ZRV condition. This would simulate a prototype skimming vessel, underway in a still lake or estuary. The test apparatus is sketched in Figure 11 and a photograph of the 75-foot-long truck and mock-up arrangement during tests is shown in Figure 12.

The best data was collected when an additional truck was employed to travel down the canal, applying oil to the waters' surface sufficiently ahead of the mock-up to allow a smooth and non-turbulent oil layer to form before encounter by the ZRV belt. This truck, complete with oil storage, pump and distribution nozzle is shown in Figure 13 and the nozzle alone is shown in Figure 14.

Performance Test Scheme

The test procedure, found to be most viable for these Part A (Houston) tests is summarized in Table 5. The collection of a "steady-state" sample representing approximately 300 feet of oil slick encountered was desired. The applied slick length was actually 100-200 feet longer (to

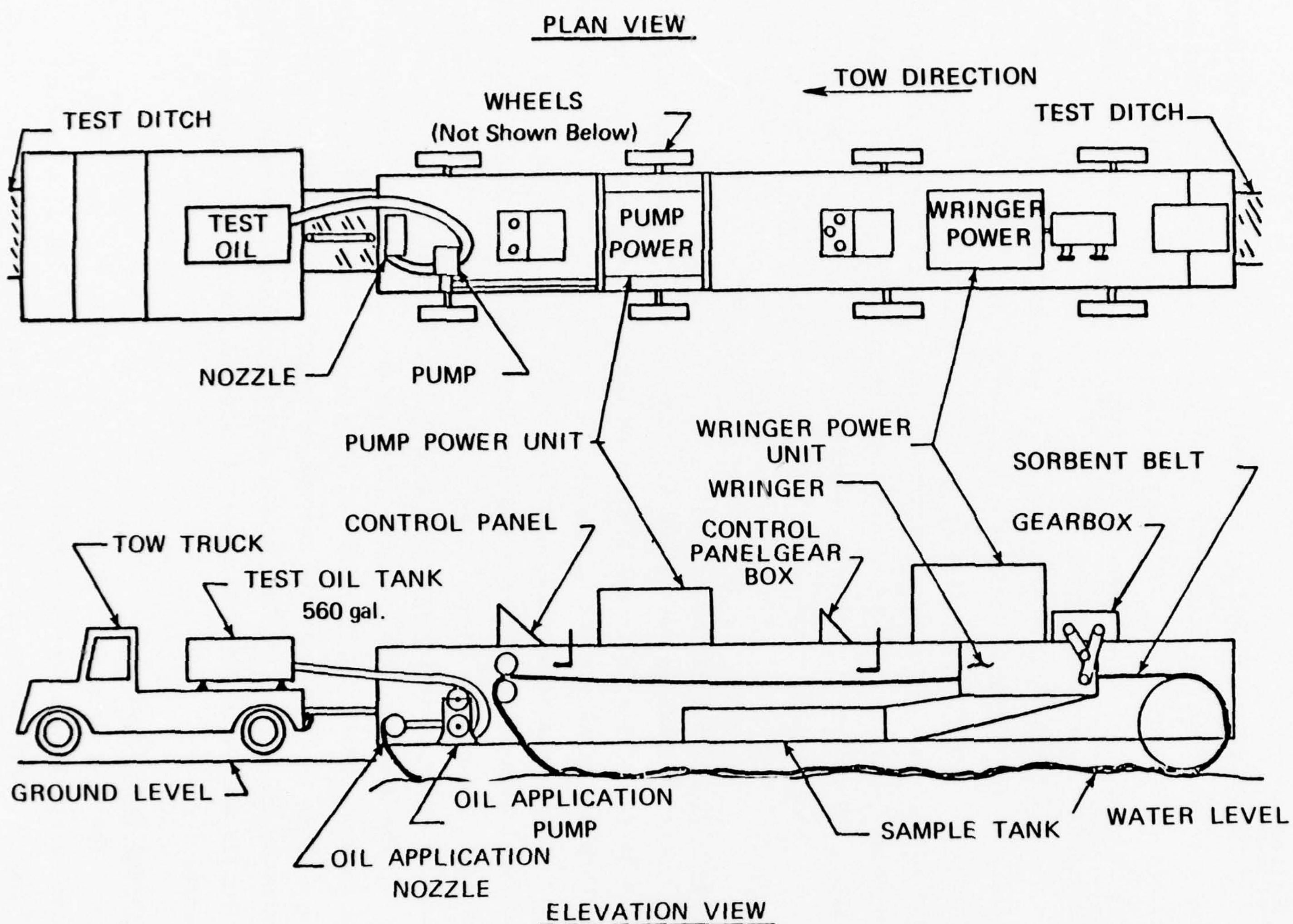

Figure 11. ZRV Test Apparatus: Houston Tests

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Figure 12. ZRV Mock-Up and Tow Truck in Houston

Figure 13. Oil Distribution Truck

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Figure 14. Oil Distribution Nozzle

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TABLE 5

ZRV MOCK-UP TEST AND SAMPLING PROCEDURES - HOUSTON TEXAS

1. Check equipment for readiness.
2. Start oil distribution pump[a]. Oil supply valve must be closed.
3. Oil-wet belt for approximately 2 minutes[b].
4. Open oil supply valve and proceed spreading oil on the test canal with oil distribution truck.
5. Begin towing the mock-up at the test engineer's signal. The mock-up should encounter the oil approximately one minute after it is released from oil distribution truck.
6. Bring the mock-up and sorbent belt up to speed.
7. Begin sample collection at the starting mark of the 300 foot test section.
8. Stop sampling at the 300 foot stop-sampling mark of the 300 foot test section.
9. Bring the mock-up to a gradual stop.
10. Check air, water, and oil temperatures. Record sample time from automatic stopwatch.
11. Transfer samples to calibrated tanks then measure total liquid depth.
12. Cover tanks and allow samples to separate overnight.
13. Drain free water then measure oil depth.
14. Stir samples in calibrated tanks then immediately catch a small sample for centrifuge analysis. This sample should be taken from the center of this large sample with a small plastic bottle.[c]
15. Skim unrecovered oil off the test canal.

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a) Originally oil distribution was begun at the start of the tow using the pump on the mock-up. Oil was encountered immediately after release. This was unsatisfactory since oil was mixed in the water column as the belt passed over. Later oil was measured out onto eight 50-foot sections of the test canal well before starting the tow. This was also unsatisfactory because wind pushed oil against the barriers separating the sections. This produced an uneven slick thickness.

b) Oil-wetting consisted of pumping oil directly on the belt in front of the wringer. The belt was run at 150-200 ft/min.

c) Centrifuge analysis was not done on all No. 2 oil samples since they separated relatively easily. Little water was found in those centrifuge samples analysed.

ensure steady-state conditions) but the flow of recovered oil was diverted to the sample recovery tank only for the sampling length. The remainder of recovered fluid (before and after sampling) was routinely drained from the recovery area to the water behind the traveling mock-up. Using this procedure the actual sample time for a given run was approximately 46 seconds for a 4 knot run and 23 seconds for 8 knots.

In the early part of the tests (the first 4 runs) a second truck for oil application was not used. The oil distribution nozzle shown in Figure 14 was attached at the front of the mock-up, approximately 10 feet in front of the sorbent belt entry point. Later, for the next 2 runs, it was placed completely in front of the mock-up tow truck (35 feet in front of the belt entry point). Results from these tests, particularly at speeds above 4 knots, were found by later tests to be invalid. Low oil recovery rates and low recovery efficiencies resulted because the nozzles caused unnatural flow turbulence. Resulting oil-water mixing occurred--even with no structural parts piercing the water and with the nozzle 35 feet in front of the belt.

Test velocities in the Houston tests ranged from 4 to 8[a] knots. Test oils used were diesel fuel oil and two blends of an LVI (Low Viscosity Index) asphaltic base, cutting stock and diesel oil. These were proportioned to closely simulate the viscosity/specific gravity/surface tension properties of residual fuel oils[b]. Properties of the three test oils--called "light", "medium", and "heavy" for their viscosity (or specific gravity) characteristics are as follows:

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a) At speeds in excess of 8 knots (1) excessive vibrations due to misalignment in the wringer drive train appeared and (2) the tow truck driver was concerned about course keeping down the canal.

b) Residual fuel oils were not readily available in the quantities needed for test. The components blended, however, are fractions present in No. 6 Fuel Oil.

TEST OIL PROPERTIES

Oil Type	Viscosity	Specific Gravity	Surface Tension	Interfacial Tension
"Light" (Diesel)	2.7 cp @ 100F 3.4 cp @ 80F	S.G. = 0.85 = 0.86	28 dyne/cm	27 dyne/cm
"Medium" (Blend)	105 cp @ 100F 183 cp @ 80F	S.G. = 0.94	ca.30 dyne/cm	ca.30 dyne/cm
"Heavy" (Blend)	467 cp @ 100F 1055 cp @ 80F	S.G. = 0.95	ca.30 dyne/cm	ca.30 dyne/cm

Using the collected sample temperature as basis for determining the actual oil viscosity for each test run, viscosities of 2.5 to 3.4 cp were determined for the light oil tests, 94 to 140 cp for medium and 520 to 850 cp for heavy.

Performance Test Results

A complete listing of all tests run and data collected in the Houston test series is placed in Appendix B. Table 6 contains data for test runs using a 3mm applied slick thickness in which essentially all oil encountered was recovered (for 3mm slicks) at speeds of 4 and 6 knots. In this case the throughput efficiencies[a] ranged from a low of 91% to a high of 110%, the higher value being above 100% either because of experimental error or because the belt encountered more oil than its width would suggest. Oil recovery efficiencies[b] were lowest for the light oil, 38 and 45% (at 4 and 6 knots) and highest for the heavy oil, 61 and 72%. The data consistently showed higher oil recovery efficiencies at higher speeds, as expected. Increased centrifugal force at the rear drum caused by higher speeds throws off loosely held water which would be retained and collected at lower speeds.

Table 6 also shows maximum recovery rates of 170, 152 and 148 gpm for the light, medium, and heavy oils respectively, all at a 6 knot and 10mm oil application rate. Corresponding recovery efficiencies were 85 to 88%. Since the volume of oil encountered was greater than the apparent belt capacity of 5.7, 5.1, and 4.9mm for the three oils, the remainder of the 10mm oil slick remained behind.

If the belt capacity were independent of speed then the recovery rate for a 4 knot, 10mm run would be 4/6 of the 6 knot result. This is approximately true for the light oil (104 gpm recovered vs 113 gpm based on

a) Throughput efficiency = oil volume recovered vs oil volume encountered x 100%.

b) Recovery efficiency = oil recovered vs oil-water mixture recovered x 100%.

TABLE 6

SIGNIFICANT RESULTS ZRV MOCK-UP TESTS IN HOUSTON

Oil Type	Test (Ref.)	Vel. Knots	Oil Thick. Applied mm	Oil Thick. Recovered mm	Oil vs. Total Fluid Recovered %	Oil Recovery Rate gpm	Throughput Efficiency %
Light (No. 2 Fuel, < 5 cp)	23	4	2.9	-	38	57	98
	14[b]	4	10.0	5.3	81	104	-
	24	6	2.9	-	45	91	105
	26	6	10.0	5.7	85	170	-
	21[b]	8	10.0	2.6[a]	84	104[a]	-
Medium (Blend, 94 to 140 cp)	32	4	3	-	54	65	110
	34	4	10	7.1	91	141	-
	33	6	3	-	65	90	100
	35	6	10	5.1[a]	87	152[a]	-
Heavy (Blend, 520 to 850 cp)	28	4	3.5	-	61	61	91
	30	4	10	8.0	82	155	-
	29	6	3	-	72	91	101
	31	6	10	4.9[a]	88	148[a]	-

a) There was substantial oil falling off rear drum. Recovery rate can be increased by using oil catching tray at rear drum to catch fling-off.

b) Mechanical improvements were made after run 22, thus performance may be lower than with improvements.

scaling down 6 knot rate) but not so for the other two oils. For these the recovery rates at 4 knots (10mm) are almost the same as the corresponding 6 knot results. This results in 7.1 and 8.0mm belt thickness capacity for the medium and heavy oils at 4 knots in contrast to 5.1 and 4.9mm thicknesses at 6 knots. Four possible explanations why medium and heavy oil recovery rates of the mock-up in 10mm slicks did not improve when the velocity was changed from 4 knots to 6 knots are:

1. Increased flow turbulence of the surface-piercing rear guide plates and forward guide rollers at 6 knots as contrasted with that at 4 knots causes the medium and heavy oils to form droplets below the surface more readily than for the light oil. As a result oil recovery is impaired.
2. If the slick is viscous and much thicker than the belt can lift off the water's surface, the hanging oil will break from the belt as close to the belt as possible because that location has the greatest oil weight hanging below. As a result oil recovery is impaired. In this case excessive oil is pulled away from the belt while only that oil locked in the fibers will remain for recovery.
3. A third argument, similar to (2), is that at higher speeds and with more viscous oils, air enters the "wedge" between the forward belt entry location and the oil layer on water. This causes a blanket of air to be locked between the belt on top and oil below. As the belt is withdrawn the air interface separates and the oil layer below it drops off. Truly this belt containing viscous oil in its pores cannot readily "breathe".
4. One explanation concerns sampling: Large volumes of viscous fluid expelled by the wringer may not drain to the sample tank at higher speeds as quickly as either smaller volumes or less viscous larger volumes could.

Explanations 2 and 3 address fluid drag problems where the velocity effect is likely to the second power. This means that the velocity effect at 6 knots is 2-1/4 times as severe as that at 4 knots.

Unfortunately this interesting problem could not be resolved with the test facilities available and within program time constraints. But even with this anomoly unanswered the measured recovery rates are quite high and this effect is absent when smaller, more normally occurring thicknesses of 3mm are tested.

Other performance-related results contained in Appendix B indicate that small ±0.5 knot variations in belt speed with respect to tow speed do not noticeably affect the performance results. Finally, a qualitative finding is that <u>in still water</u> a tighter belt performed better than a looser one.

V. MOCK-UP PERFORMANCE TESTS - PART B (OHMSETT)

Introduction

Part B of the principal confirming tests of the ZRV Mock-Up took place at the U.S. Environmental Protection Agency's Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) located in Leonardo, New Jersey. This tank is 667 feet long by 65 feet wide and is filled to a depth of 8 feet with brackish water. Either regular or harbor chop waves can be generated in this facility. Several movable bridges are available for supporting test devices, and tow speeds up to 6 knots are attainable. A detailed descritpion of OHMSETT can be found in Reference 2.[2]

The objective of this second series of 73 test runs was to explore the effects of oil type, tow velocity and waves, as well as device settings (belt speed, rear drum height, etc.) on the performance results.

Test Apparatus and Facilities

For this series of tests the ZRV Mock-Up was suspended over the water in the test tank, supported by a forward and aft movable bridge. The trailer wheel assemblies used in previous tests were removed to provide better visibility of the test device. Oil was applied to the water in front of the mock-up using a manifold with multiple weirs, located approximately 40 feet in front of the belt touchdown point (on the water) of the mock-up. Figure 15 is a photograph of the ZRV Mock-Up (see arrow) in OHMSETT. This was taken prior to a test run toward wave generator at the far end of the tank.

Initially, two parallel oil guide plates were used to direct the slick toward the mock-up belt and prevent oil from spreading to either side, away from the belt. Because these 40-foot-long aluminum plates pierced the water to a depth of a foot or so, they created excessive water turbulence and caused oil entrainment (sub-surface droplet formation) in front of the belt at high speeds. This problem was solved by using two floating, trailing ropes instead of the plates to constrain and guide the oil slick toward the belt. Even with the guide ropes, however, parts of the oil slick were wider than the belt and the encountered amount had to be estimated.

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2. Ayers, R. R., "A Rigid, Perforated Plate Oil Boom for High Currents", EPA-600/2-76-263, December 1976, Prepared by Shell Development Company for the U.S. Environmental Protection Agency.

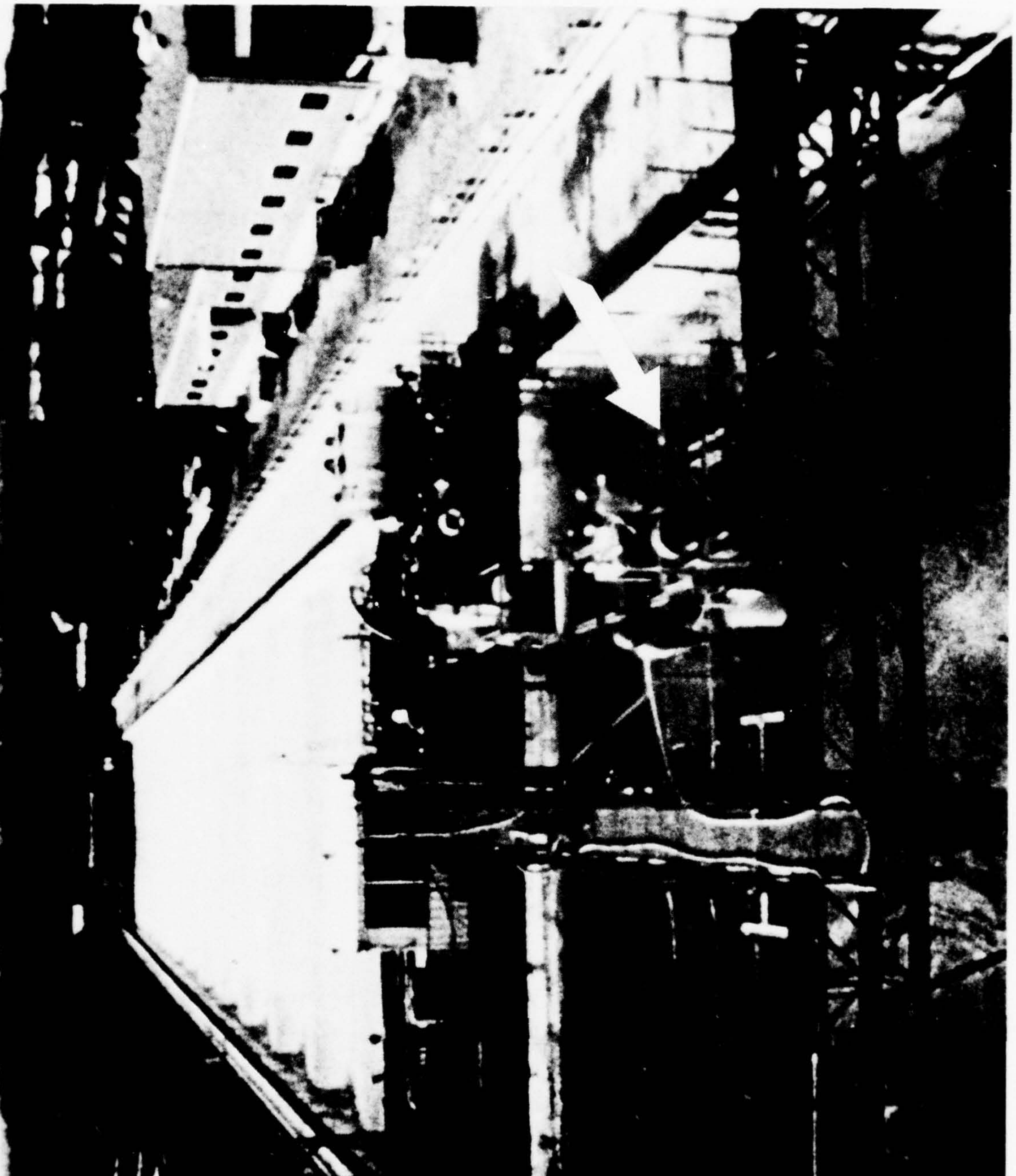

Figure 15. ZRV Mock-Up in OHMSETT

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Performance Test Scheme

The test procedure adopted for these Part B - OHMSETT tests is summarized in Table 7. A "steady-state" sample representing approximately 300 feet of tank length was collected during each test run. The tank length over which oil was applied was actually longer, but the flow of recovered oil was diverted to the sample recovery tank only for the sampling length. The remainder of recovered fluid, collected at the beginning to the test run, was allowed to gravity-drain from the recovery area to the water behind the traveling mock-up.

Two test oils were used in the OHMSETT tests. One was a low viscosity mineral oil called Sunvis 7 and the other was higher viscosity lubricating oil, Sunvis 1650. These oils were selected to simulate crude or refined oil properties, while avoiding black (asphaltic) oils. Black oils stain everything they contact and are not as suitable for reuse. Properties of the two oils are:

TEST OIL PROPERTIES

Oil Type	Viscosity	Specific Gravity	Surface Tension*	Interfacial Tension*
Sun. 7	43 cp @ 60°F 28 cp @ 80°F	0.8509	29 dyne/cm	11 dyne/cm
Sun. 1650	1950 cp @ 60°F 820 cp @ 80°F	0.8866	31 dyne/cm	35 dyne/cm

* Measured at 75°F

All of the tests were conducted at a tank water temperature of 75 ± 1°F. It can be assumed that the oil temperature during recovery was approximately the same as the water temperature.

Performance Test Results

A complete listing of all tests performed and the data collected during the OHMSETT test series is included as Appendix C. Table 8 contains selected test results, grouped so that data interpretation is made easier. Test runs were selected for Table 8 based on whether they were considered representative runs; runs in which no test-related problems occurred which might confuse the interpretation and prevent the extrapolation of results.

TABLE 7

ZRV MOCK-UP TEST AND SAMPLING PROCEDURES
OHMSETT TESTS

1. Check equipment for readiness.

2. Start wave generator if called for in test plan.

3. Start the belt slowly.

4. Begin the tow and oil distribution simultaneously.

5. Bring the mock-up and belt up to test speed.

6. Begin sampling at the timekeeper's signal. The timekeeper will signal to the belt drive operator when oil is first visible on the belt entering the wringer and start his stopwatch simultaneously.

7. Photograph oil slick in front of the mock-up to later determine slick width encountered by belt.

8. Disengage the wringer drive clutch at the finish mark. The timekeeper will stop his stopwatch at this time to record sample time.*

9. Bring the tow bridge and mock-up to a stop. Stop the wave generator.

10. Lower the skimming bar and return bridge at 1/2 knot speed, pushing remaining oil back down the tank for cleanup.

11. Transfer samples to calibrated tanks. When transfer is complete pour 5 gallons of water into the sample pan to flush transfer hoses. Measure sample depth.

12. Allow sample to stand about one hour then drain free water. Measure sample depth.

13. Stir sample tank then catch a small sample for centrifuge analysis. This should be taken from the center of the main sample with a small bottle. (The 5 gallons of water added in step 11 must be subtracted from total water volume recovered to determine recovery efficiency.)

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* At the beginning of the Sunvis 7 and the Sunvis 1650 test series sampling was initiated at a starting marker and stopped at a finish marker, belt speed remaining constant through this time. The sample time was automattically recorded. This procedure was found to not represent a valid steady-state sample.

TABLE 8

SIGNIFICANT RESULTS - ZRV MOCK-UP TESTS AT OHMSETT

Oil Type and Test Purpose	Test (Ref.)	Vel. Knots	Oil Thick. Applied mm	Oil Thick. Recovered mm	Oil vs. Tot. Fluid Recovered %	Oil Recovery Rate gpm	T.E.* %
A. Sun. 7, Speed Variation	1-1	2	(3.4)	1.2	25	12	68E**
	1-2	4	(2.6)	2.0	37	40	78E
	1-4	5	(2.8)	2.2	44	54	77
	1-3	6	(3.4)	1.9	40	57	57
B. Sun. 7, Thickness Variation	2-2	6	(1.2)	1.3	32	40	115
	2-3	6	(2.8)	3.3	62	98	117
	2-4	6	(3.3)	4.1	69	124	127E
C. Sun. 7, Belt Speed Variation About 6 Knots	4-8	6, 5	(2.5)	2.3	51	68	90
	4-6	6, 5.5	(2.9)	1.4	32	41	48
	4-2S	6, 6	(2.8)	1.9	47	56	67E
	4-5	6, 6	(2.8)	1.8	35	53	58
	4-10	6, 6.5	(2.9)	1.8	37	55	60
	4-9	6, 7	(2.7)	2.4	45	73	85
D. Sun. 7, Belt Speed Variation About 5 Knots	4-12R	5, 3	(2.8)	2.4	50	60	83
	4-13	5, 4	(2.7)	2.6	50	64	95
	4-14	5, 5	(2.6)	2.1	38	53	81
	4-15	5, 6	(2.6)	1.6	40	39	82

*Throughput efficiency

** E - Percent of slick encountered estimated by observer on bridge.

TABLE 8 (Continued)

Oil Type and Test Purpose	Test (Ref.)	Vel. Knots	Oil Thick. Applied mm	Oil Thick. Recovered mm	Oil vs. Tot. Fluid Recovered %	Oil Recovery Rate gpm	T.E.* %
E. Sun. 7, Effect of 2' Harbor Chop	8-2	4	(1.6)	1.5	15	30	96E
F. Sun. 1650, Speed Variation	12-1A	2	(3.2)	3.5	81	35	109
	12-2A	4	(3.1)	3.8	79	75	121
	12-7R	4	(3.2)	3.0	62	59	133
	12-4	5	(2.1)	2.7	63	66	128
	12-4A	5	(3.0)	3.6	75	89	119
	12-3R	6	(2.8)	2.9	76	86	101
	12-8	6	(2.4)	2.4	65	72	100
	12-3A	6	(2.9)	3.2	74	97	112
G. Sun. 1650, Thick Slick	13-2	6	(4.6)	3.7	79	110	81
H. Sun. 1650, Belt Speed Variation	15-4	6, 5	(3.1)	3.0	68	89	98
	15-2R	6, 5.5	(3.0)	2.8	68	84	94
	15-2S	6, 5.5	(3.0)	2.8	68	83	90
	12-3R	6, 6	(2.8)	2.9	76	86	101
	12-3A	6, 6	(2.9)	3.2	74	97	112
	15-3R	6, 6.5	(3.0)	3.1	62	93	106E
	15-5	6, 7	(3.0)	2.5	57	75	83E

*Throughput efficiency

TABLE 8 (Continued)

Oil Type and Test Purpose	Test (Ref.)	Vel. Knots	Oil Thick. Applied mm	Oil Thick. Recovered mm	Oil vs. Tot. Fluid Recovered %	Oil Recovery Rate gpm	T.E.* %
I. Sun. 1650, Speed Variation with 2' Harbor Chop	19-1	2	(2.0)	1.8	37	18	94
	19-2	4	(2.7)	2.0	26	40	71E
	19-3	5	(2.3)?	1.8	25	46	139
	19-4	6	(2.4)	2.3	30	70	100E
J. Sun. 1650, Regular Wave Length Variation	22-1	6	(3.2)	2.0	54	60	70
	22-2	6	(2.4)	2.5	67	74	91
	22-3	6	(2.7)	2.5	48	76	94
	15-9	6	(2.9)	2.7	64	80	92

*Throughput efficiency

In general, Table 8 shows oil throughput efficiencies from 57% to 127%, recovery efficiencies from 15 to 69% and oil recovery rates from 12 to 124 gpm for the Sunvis 7 oil. Oil throughput efficiencies from 70 to 139%, recovery efficiencies from 25 to 81% and oil recovery rates from 30 to 110 gpm were measured for the Sunvis 1650 oil. Tank facility limitations prevented tow speeds above 6 knots and oil application rates above 160 gpm.

Referring now to Table 8 in more detail, Series A contains runs using the low viscosity Sunvis 7 oil in which the device tow speed was varied between 2 and 6 knots. The recovery rate increased with speed over the entire range but it did not improve appreciably between 5 and 6 knots. Throughput efficiencies were between 68 and 78% for speeds below 6 knots, however the 6 knot result was only 57%. Thus, this series shows a deterioration in performance at higher speeds, with the 6 knot results essentially the same as the 5 knot ones.

Series B contains runs in which the applied oil thickness varied between 1.2 and 3.3 mm at a tow speed of 6 knots. The throughput efficiencies are high--above 100%--indicating that (a) there are measurement errors and (b) essentially all of the oil encountered was recovered, independent of slick thickness. In the 3.3 mm slick the oil recovery efficiency was 69%, while at 1.2 mm, it was only 32%. This shows that the remaining fluid volume capacity of the belt (after the oil is sorbed) tends to fill with water. Greater thicknesses could not be applied because this low viscosity oil spread out before it reached the belt.

Comparing related runs from Series A and B, one finds that the recovery rate and the throughput efficiency for Test 2-4 was much greater than for equivalent Test 1-3. Probably the reason for this discrepancy is that the belt encountered more oil in Test 2-4 than the 3.3 mm average slick thickness (used to calculate throughput efficiency) would indicate. The flow rate from the oil distribution manifold was increased in Test 2-4 to produce an 8 mm slick. However, the Sunvis 7 slick spread rapidly and was considerably wider than the belt when the mock-up reached it. With the measurement equipment available only an average slick thickness could be determined based on slick width, manifold flow rate, and tow speed. The actual slick was thicker in the center and thinner on the edges. Thus, the belt, running through the center of the slick, encountered more oil than could be accounted for using an average

slick thickness. This produced an abnormally high throughput efficiency and the large recovery rate. Also, it is likely that in the thicker center of the slick the oil concentration was high with relatively little water available for belt sorption. Therefore, recovery efficiency was higher in Test 2-4 than in Test 1-3.

Series C test runs were performed at a 6-knot tow speed to find out how changes in belt speed with respect to the tow speed (non-ZRV conditions) affect recovery performance. Based on the throughput efficiency results, better performance was attained at ± 1 knot belt speed difference from ZRV conditions for Sunvis 7. At these speeds the throughput efficiencies were 85 to 90% and corresponding recovery efficiencies were 45 to 51%.

Series D test runs were performed for the same purpose as Series C however the nominal tow speed was 5 knots. This set of runs shows that best performance was obtained by running the belt one knot slower than ZRV, otherwise the results were constant from -2 knots differential (belt slower) up to +1 knot differential.

The one test run included in Series E is a 4 knot ZRV run in a 2-foot harbor chop wave pattern. The throughput efficiency was 96%, indicating that all the oil approaching the belt was recovered, but the recovery efficiency was low--15%--caused by choppy waves splashing water over the belt.

The remaining test series in Table 8 were run using Sunvis 1650 oil, the more viscous of the two test oils. Series F explored the effects on performance of variations in tow speed at ZRV. Since all of the throughput efficiencies were 100% or better for tow speeds from 2 to 6 knots, it can be said that the oil collection performance was insensitive to tow speed. An additional result is that the recovery efficiency is approximately proportional to the encountered oil thickness.

An oil thickness of 4.6 mm was applied to the water in front of the skimmer in the one test run comprising Series G. This was the thickest slick that the oil application pump could produce. At 6 knots this resulted in an oil recovery rate of 110 gpm and a recovery efficiency of 79%. The throughput efficiency was 81%, indicating, if this one figure is accurate, that this percentage of the applied oil slick thickness--3.7 mm--is the belt sorption capacity for this oil. One can compare this result with runs 12-3 and 12-8 in Series F to see that recovery performance is proportional to applied oil thickness (at a 6 knot speed in this case).

Series H, also using Sunvis 1650 oil, explored variations in belt speed while the tow speed was a constant 6 knots. These runs all have high throughput efficiencies over a ± 1 knot belt speed difference range, but performance looks best exactly at ZRV, since the recovery efficiency is best there.

In Series I, tow speeds were varied between 2 and 6 knots with the belt speed at ZRV in each case. The added test condition here is two-foot harbor chop waves. The throughput efficiencies were high, above 71%, for all speeds, and as previously found for Sunvis 7, the recovery efficiencies (25 to 37%) are lower than those for smooth water. The performance results under choppy wave conditions are more erratic than under calm water conditions because it was much more difficult to determine how much oil was actually encountered by the belt.

Finally, Series J treats the effect of regular waves on skimmer performance at 6 knots. These runs show that regular waves had no significant affect on performance when compared with calm water results.

VI. COMPARISON OF TEST RESULTS

Introduction

The purpose of this section is to compare the ZRV Mock-Up performance results from Part A (Houston) tests with Part B (OHMSETT) results and discuss their significance in projecting the ZRV Prototype performance. Recall that the Part A tests were performed in a test canal 3 feet wide and 875 feet long filled with one foot of fresh water, while the Part B tests were performed in a test tank 65 feet wide and 667 feet long filled with 8 feet of brackish water.

Test Differences

A major difference in the test scheme was that in Part A oil was applied using multiple nozzles mounted on a separate oil distribution truck running approximately one minute ahead of the test device, while in Part B oil was applied using a multiple-weir oil distribution manifold placed 40 feet in front of the mock-up. The one minute delay between oil application and mock-up encounter in Part A tests was equivalent to placing the oil distribution nozzles 608 feet in front of the mock-up at a 6-knot tow speed. In contrast, oil was applied only 40 feet in front of the mock-up at speeds up to 6 knots for the Part B tests. Thus, one would expect that the mock-up would encounter a smoother and more uniform and continuous slick in the Part A (Houston) tests than in the Part B (OHMSETT) tests.

The other significant difference in the two test parts was in the oils that were used. Blends of refined oils were used in Part A, while a mineral oil and a lube oil were used in Part B. The significant differences between these oils (compare tables on pages 40 and 46) are:

1. The mineral oil, Sunvis 7, used in Part B has a viscosity of 28 cp at 80°F while the diesel oil used in Part A was only 3.4 cp. Based on the Stage I studies, this should not significantly affect a comparison of results, since the specific gravities of the two oils are about the same.

2. Surface tensions of the two oils, Sunvis 7 and diesel, are about the same, but the interfacial tension of Sunvis 7 is quite low--11 dynes/cm--when compared with 27 dynes/cm for diesel oil. Oils with low interfacial tensions will tend to mix more readily

with water and make oil/water separation more difficult after mixing.

3. Sunvis 1650 oil, also used in Part B tests, has viscosity and surface (including interfacial) tensions similar to the "Heavy" blend used in the Part A tests, but Sunvis 1650 has an obviously lower specific gravity (0.887) than that (0.950) for the "Heavy" oil. In skimmer oil loss mechinisms governed by density effects, performance will be poorer for denser oils.

Specific effects of these differences on comparisons of results between Parts A and B tests will be discussed further.

Tests With Low Viscosity Oils

Figure 16 is a graph of oil recovery rate vs. tow speed using data from tests with Sunvis 7 from Table 8 and with diesel oil from Table 6. The solid diagonal line represents the oil recovery rate expected for a 3 mm oil slick by assuming that the throughput efficiency is 100%. For better data comparison, the data points shown in the graph have been slightly modified from the tabular values in order to convert results from slick thicknesses near 3 mm to equivalent results for 3 mm. This conversion was done simply by multiplying the near-3 mm oil recovery rate by a ratio of the actual and desired (3 mm) thickness.

One can see that the two data points from the Part A (Houston) tests fall quite close to the predicted value, while data points from the Part B (OHMSETT) tests are significantly lower than the prediction, except for two points at 6 knots. The two high data points at 6 knots represent tests run to determine oil recovery performance in thicker slicks using Sunvis 7 oil. The problem with these two runs was that when attempting to apply a 5 and 8 mm slick in front of the mock-up, the oil emanating from the manifold simply spread out to a wider, thinner slick than desired in the 40-foot distance between the manifold and the sorbent belt. The applied oil thickness approaching the belt was computed from the known oil application pump rate and an estimate of the slick width approaching the belt. The thickness computed this way is likely lower than the actual thickness because, at least qualitatively, the slick was thicker toward the middle, the portion which the belt encountered.

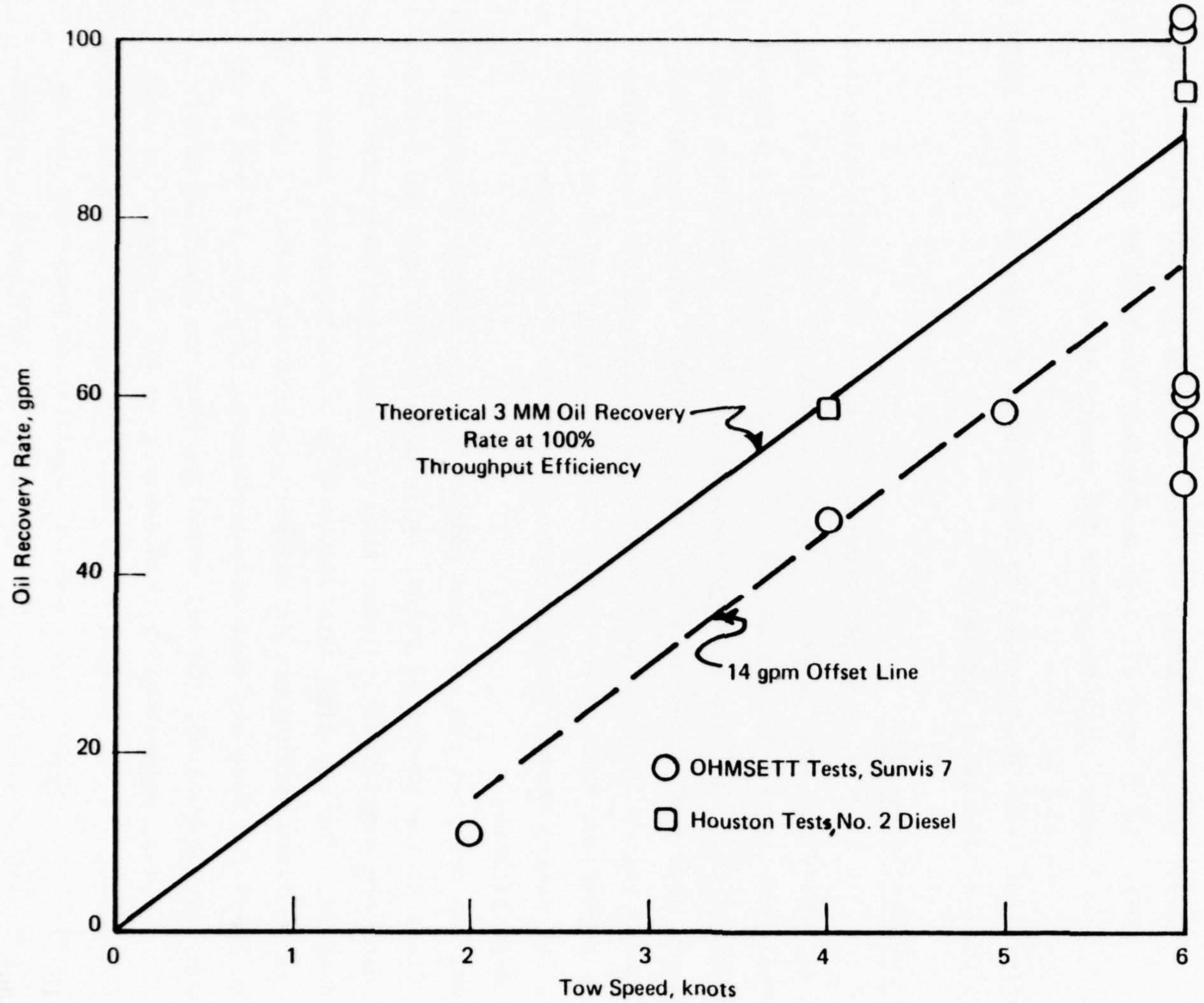

Figure 16. Data Comparison - Tests with Low Viscosity Oils

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Consequently, the recovered oil thicknesses computed from the measured oil recovery rates for runs 2-3 and 2-4 of Series B tests (Table 8) were 3.3 and 4.1 mm, respectively, while the corresponding applied oil slick thicknesses were lower--2.8 and 3.3 mm. So the two high data points for Sunvis 7 oil at 6 knots in Figure 16 are high because the actual oil slicks were approximately 20% thicker than 3 mm.

The remaining data points for Sunvis 7 oils, and specifically the points for tow speeds between 2 and 5 knots, show oil recovery rates that are lower than the predicted rates by about 14 gpm (see dashed line). The primary discrepancy here is very likely due to the abnormally low interfacial tension of the Sunvis 7 oil. Based on qualitative underwater observations of the applied oil slick approaching the mock-up belt, a one-or-two-inch thick mixture of oil droplets in a water medium actually approached the belt. Such a mixture is much easier to form with low-interfacial-tension oils than with oils having a higher value. It appeared that the oil droplets eventually contacted the belt farther back along its water contact length. However, the belt, at the point where it contacts the water's surface, will sorb the mixture approaching it rather than just the oil. Although the remaining droplets below the surface rise quickly toward the floating belt, there is little remaining sorption capacity. Therefore, the low interfacial tension of the Sunvis 7 oil is the likely primary cause of the discrepancy between Part B results and those for Part A.

Another possible cause for differences in Part B test results could be problems with estimating and measuring the amount of oil applied that should be encountered by the mock-up belt. It is difficult to say whether the errors involved would cause higher or lower results.

Finally, turning to the four apparently low data points for Sunvis 7 at 6 knots, there are likely two major causitive factors involved. One factor is the low-interfacial-tension problem discussed previously. But the other factor is believed to be turbulence and subsequent oil entrainment caused by the applied oil impacting the water surface too near to the test device to allow the slick to coalesce on the surface. The actual mechanism involved is fluid drag caused by the oil layer flowing toward the water and piercing it, as well as oil entrainment caused by the high interfacial shear forces. Drag forces are proportional to the square of velocity so it is not unusual for this turbulence to become a problem at 6 knots, where it was not apparent at

5 knots. Also, the mass rate of flow of oil increases linearly with velocity, further contributing to drag, turbulence and oil entrainment problems.

This problem was initially discovered in the early Part A tests in the canal at Houston, Texas, when nozzles were at first attached in front of the test device. The test-related problem appeared during tests with diesel oil at speeds above 4 knots and resulted in lower-than-expected oil recovery rates. It was made negligible for the Part A tests by applying the oil (by a separate vehicle) much earlier in time before the belt contacted it. Further, the problem was anticipated during the Part B tests at OHMSETT, but using a similar scheme to avoid it was considered impractical. An important consideration was that the other skimmer devices under concurrent development by the USCG were previously tested using the same oil distribution system. Consequently, quantitative comparisons between the devices would have been invalidated by changing this test fixture design only for the ZRV Mock-Up, the last device tested in the program.

In summary, discrepancies between Part B tests with Sunvis 7 oil and Part A tests with diesel oil were likely caused by these problems:

1. The low interfacial tension of the Sunvis 7 oil caused the belt to contact an oil-water mixture rather than an oil lens on water.
2. At tow speeds above 5 knots, water turbulence, fluid drag forces and oil entrainment problems caused by the oil application manifold being too close to the mock-up resulted in oil recovery rates even lower than those attributable to low interfacial tension effects alone.
3. When attempts were made to apply thick (5-8mm) slicks in front of the device at 6 knots, a continuous oil layer appeared on the water's surface, unlike that which occurred with 3mm thicknesses of Sunvis 7, but (a) the slick spread too wide before it reached the belt, and (b) the slick was much thicker toward the center, where it contacted the belt, than predicted using a uniform slick thickness assumption. The positive effect of this thickened surface layer on the oil recovery rate was apparently so strong that it overcame the negative effect described in 1) and 2) above.

So, all of the discrepancies in results were related to either a test fixture or a test oil. The test oil problem, namely low interfacial tension, was merely an obstacle in interpreting test results. But it could be of significance in real spill situations where surfactants in the water are

concentrated enough to lower the spilled oil interfacial tension, and accordingly reduce the skimmer recovery performance (and cause stable oil in water emulsions). The fixture (distribution manifold) problem was solely a test-related problem.

Tests with High Viscosity Oils

Figure 17 is a graph of oil recovery rate vs. tow speed, similar to Figure 16, except that this data is for the higher viscosity test oils (medium blend, heavy blend and Sunvis 1650). The theoretical line is the same and the test data has been adjusted to reflect a 3mm thickness. In this figure both the Part A (Houston) and Part B (OHMSETT) results agree in general with the 100% throughput efficiency prediction line.

If there is any inaccuracy involved other than the usual errors associated with oil recovery performance tests of this type, it could be in estimating the applied slick thickness approaching the belt in the Part B tests. If the slick thicknesses approaching the device were consistently underestimated, the result would be a number of data points exceeding the 100% throughput efficiency line, as occurred in this case. Oil distributuion turbulence effects as found in the Sunvis 7 tests at 6 knots were not an obvious problem here because the interfacial tension was higher and more normal. The higher viscosity oils tended to form floating lenses on the water more easily, without as much entrainment. Also, if droplets of this relatively low density Sunvis 1650 oil were entrained and did rise toward the belt they would more readily attach to it. If the Sunvis 1650 oil had been as dense as the refined oil blends used in the Part A (Houston) tests, there likely would have been greater entrainment problems due to the oil distribution manifold and consequently lower-than-predicted oil recovery rates.

Measurement Errors

An in-depth study of test errors for Parts A and B of the test program, was not part of the program objectives; however, some general comments can be made in this regard. Referring to Figures 16 and 17 again, if (a) there were no errors in controlled variables such as tow speed and pump rates, (b) the oil slick approaching the belt was just as wide as the belt and of uniform thickness and (c) the sampling procedures and measuring techniques were perfectly accurate, then no data points should fall above the 100% throughput efficiency line. Since data points did, in fact, exceed values

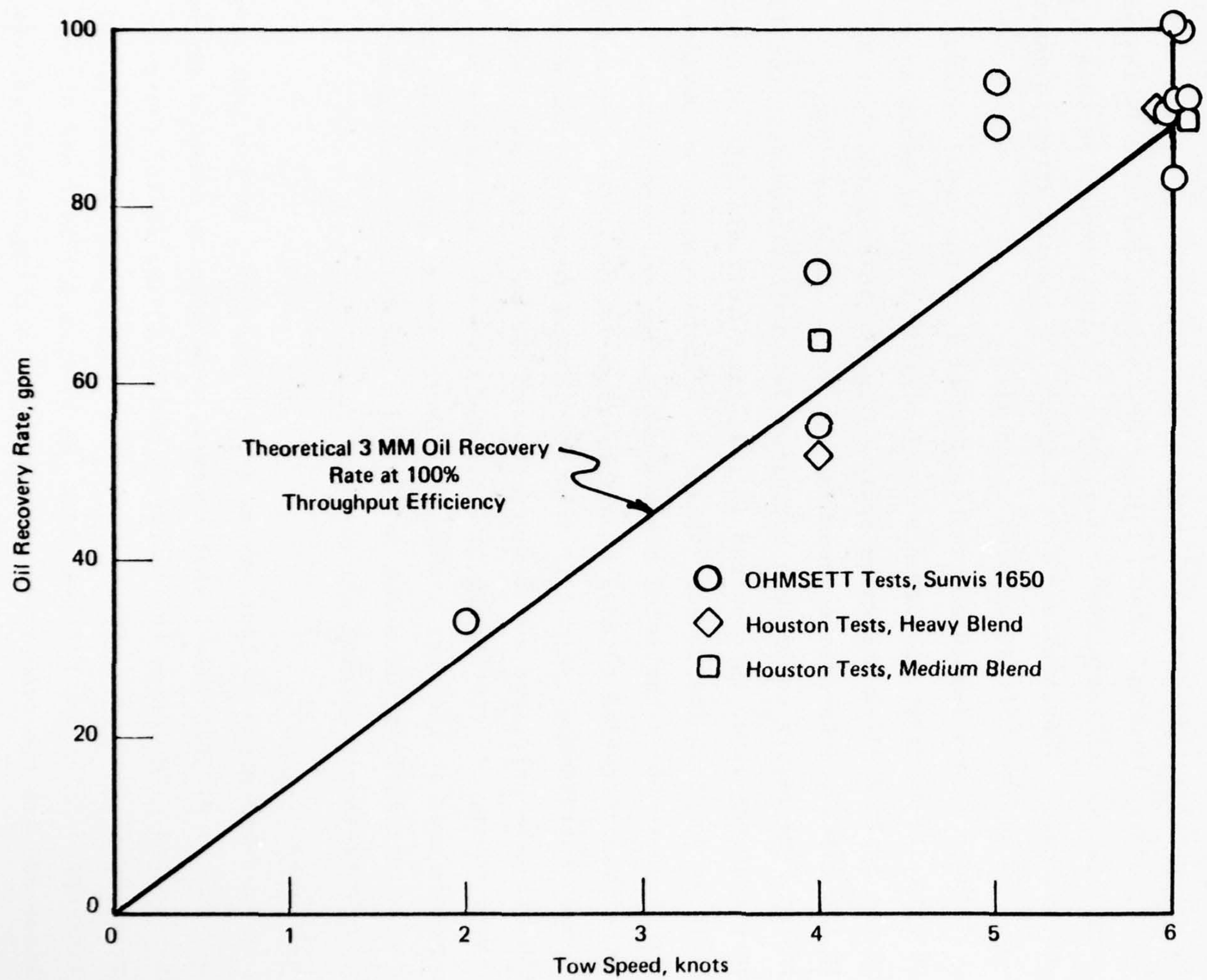

Figure 17. Data Comparison – Tests with High Viscosity Oils

01236

predicted by this line, one can perhaps assume that the combined errors, including those of accuracy and precision, are approximately equal to the standard deviation of the high data points from the 100% line. Thus, measurement errors for these tests were ± 16.5% for the OHMSETT tests and ± 10.4% for the Houston tests. Low points cannot be used in the calculation because the discrepancy can be due to the inefficiency of the skimming device in collecting the oil, which is not a measurement error.

VII. VESSEL MODEL TESTS

Introduction

A 1/8-scale model of the ZRV catamaran vessel design was designed by Alan C. McClure Associates and tested in the Davidson Laboratory Tank at the Stevens Institute of Technology in April, 1976.

Objectives of the test program were to (1) verify vessel resistance predictions (2) detect any between-hull turbulence deemed detrimental to skimming and (3) determine the effects of waves on vessel resistance and motions. Additionally the belt interaction with the vessel was studied in a qualitative way, since powered twin belts were modeled.

Summary of Results

Smooth water performance showed vessel resistance about as expected and demonstrated an almost complete lack of disturbance in the water surface between the pontoons where the skimmer belts operate. Initial tests in head seas indicated excessive slamming of the center section. Later the forward end of the center section was elevated about two feet (full-scale), resulting in satisfactory performance. Tests in following seas showed very satisfactory performance. Motions at zero speed in waves from various directions confirmed the design.

Design changes resulting from the test findings included raising the forward end of the center section about two feet, increasing the freeboard of the pontoons forward about a foot, and decreasing the transom immersion slightly.

In operating the model skimmer belts, it was essential to provide guide plates on both sides of the belt to keep it centered on the drum. These need be only about a foot long (full-scale), placed close to the drum. For the model belts at least, the belt interaction with the water is very sensitive to belt tension. Excessive slack may result in large amounts of water pick up and high drag. Raising the forward part of the center section, and hence the belts, seemed to improve belt wave conformance.

Model

Figure 18 shows a sketch of the general configuration of the model with prototype dimensions indicated. The hulls were shaped from solid high-

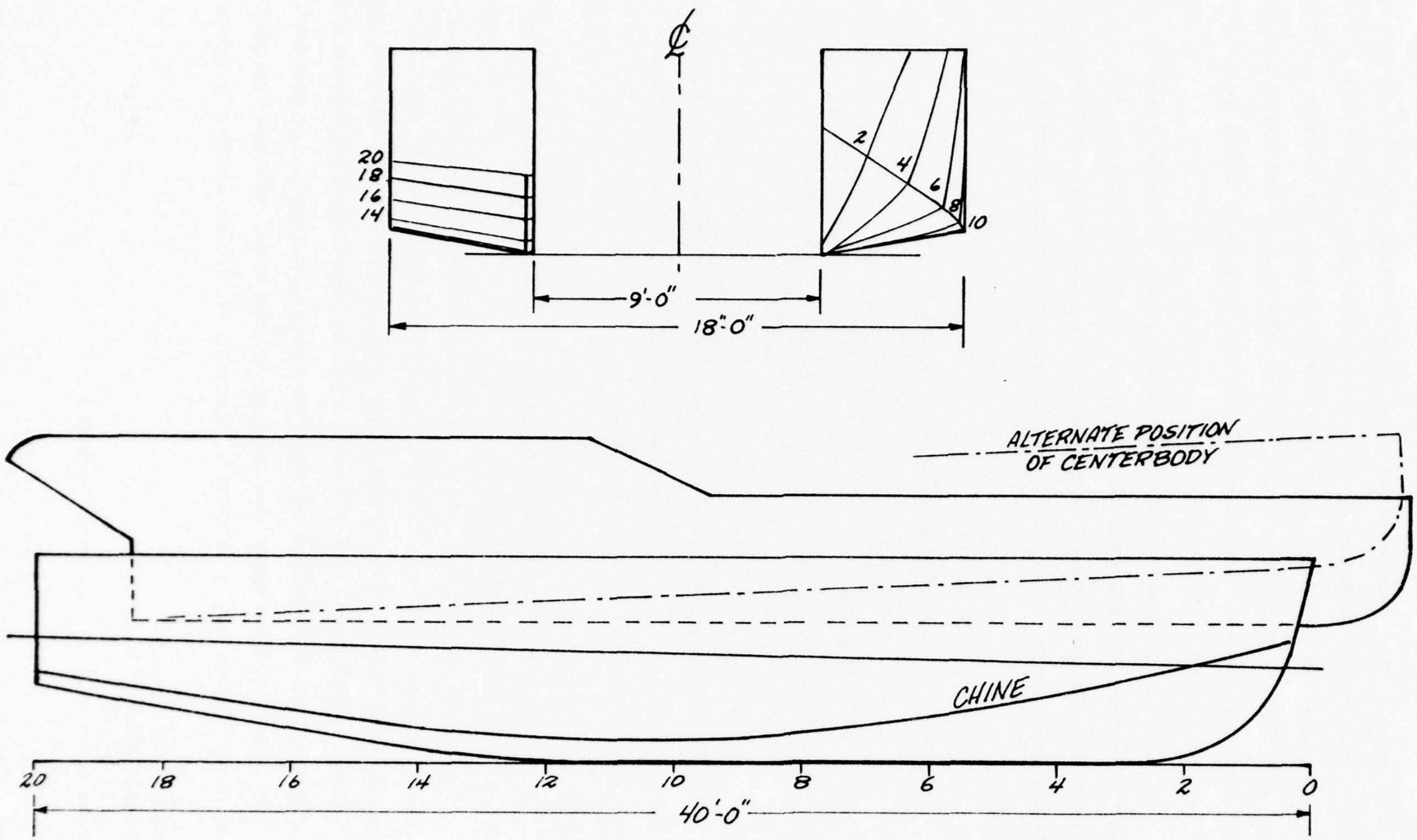

Figure 18. Vessel Model Configuration

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density foam plastic and connected by a centerbody structure made of plexiglass sheet. Figure 19 is a photograph of the model attached to the towing carriage; although the skimming belts are not in place, the driving rollers at the bow and the stern rollers are visible. The bow rollers were driven by a dc motor with adjustable speed control. The two endless belts were of non-wetting, woven synthetic fabric.

Davidson Laboratory installed a towing yoke assembly spanning the centerbody structure and attached to pivots on each hull (Figure 19). Lead shot ballast was placed in three compartments in each hull; additional ballast weights were placed on deck. The following prototype condition was represented:

Draft, Sta. 0, ft	3.15
Sta. 20, ft	3.95
Displacement, lb	50,090
LCG* fwd Sta. 20, ft	17.63
VCG above BL, ft	5.50
Pitch gyradius, ft	9.63
Roll gyradius, ft	5.44

Free oscillation tests were conducted in still water and natural periods were measured. The prototype periods are as follows: 2.53 sec for 4 pitch cycles; 2.73 sec for 5 roll cycles.

Test Procedures

All testing was conducted in Davidson Laboratory Tank 3 in fresh water with a temperature of 69°F.

In smooth water, drag, trim and heave at the CG were measured. Signals from the drag balance, trim clinometer and heave pulley were transmitted by overhead cables from the towing carriage to shoreside signal conditioning units. Conditioned signals were time-averaged on the tankside PDP-8e digital computer which produced teletype printouts of results in engineering units. Since the towing thrust was applied to the model through the pitch pivots on deck, Figure 19, a prototype distance of 5.5 ft above the designed

*CG = Center of Gravity
LCG = Longitudinal CG
VCG = Vertical CG
BL = Base Line (Lowest Point of Pontoon)

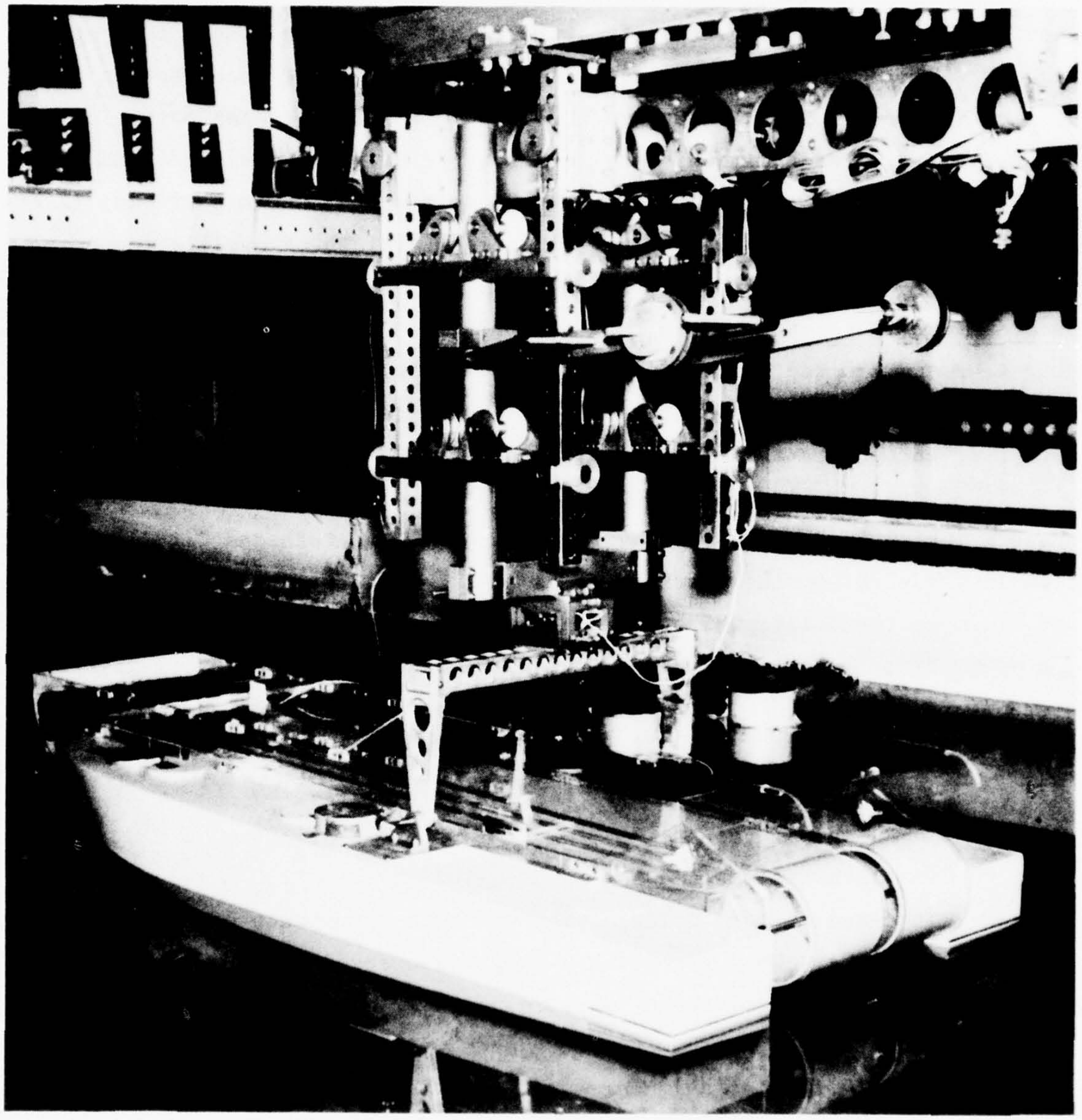

Figure 19. Vessel Model in Test Tank

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shaft line, an artifical bow-down moment equal to 5.5 times the drag was induced. Ballast weights were shifted prior to each run to cancel this moment.

During towing tests in waves, drag and vertical acceleration at the CG were measured. Signals were recorded on chart paper and on magnetic tape. After digitizing each time history on-line, the computer evaluated and averaged the peaks and troughs, printing out a mean value, and significant (average of 1/3 highest) and average of 1/10 highest values of oscillation peaks and troughs; the number of oscillations was also recorded. Data were recorded during constant speed runs of 150 ft in tank length when running in head seas and 130 feet in following seas. At higher speeds, multiple runs were taken in different sections of the wave pattern to obtain an adequate number of encounters for statistical reliability.

Runs were made at zero speed in head, 45° bow, and beam seas to observe motions and general behavior. The model was tethered with light fishline-and-coil-spring moorings so as to maintain the desired heading angle and minimize the drift, while not interfering with the oscillatory motions.

Prior to conducting the wave tests, two reproducible irregular sea states were calibrated. From chart record time histories of the 100 waves in each sea state, the following characteristics were determined.

Significant height, ft	1.95	3.85
Maximum height, ft	3.35	4.80
Average period, sec	2.60	3.50

Time-scaled 16mm color motion pictures were taken of portions of selected test runs. When viewed at a projection speed of 16 frames per second the prototype time scale is represented.

Two runs in smooth water were made with only the port side belt in place and being driven at a linear speed about equal to the model towing speed, i.e., so the relative velocity was near zero between the lower loop of the belt and the water.

The final six runs of the test program were made with the center-body structure raised at the forward end as shown in the sketch of Figure 18.

Test Results

Table 9 lists all the runs made during the test period in Tank 3. Note that except for Runs 19 and 20, skimming belts were not installed.

TABLE 9

TABLE OF RUNS
IN
SMOOTH WATER

Run	Trim Aft ft	Centerbody Position	Speed kt	Remarks
1	0.8	Original	4	Thrust moment incorrect
2			6	
3			8	
4			9	
5			10	
6			11	
7			4	
8			6	
9			8	
10			7	
11			7	
12			8	
13			9	
14			10	
15			11	
16	Zero		7	
17			8	
18			9	
19	0.8		7	Port belt running
20			7	Port belt running
30			7	Movie run; no data
31			9	Movie run; no data
36		Raised	8	
40		Raised	12	

TABLE 9 (cont'd)

TABLE OF RUNS
IN
ROUGH WATER

Run	Centerbody Position	Significant Ht. and Heading	Speed kt	Remarks
21	Original	2' Head	7	Aborted
22			4	
23			6	
24			6	
25			7	
26			7	
27			4	Movies
28			6	Movies
29			7	Movies
32		2' Following	7	Movies
33		4' Head	0	Movies
34		4' Bow	0	Movies
35		4' Beam	0	Movies
37	Raised	2' Head	6	Movies
38		2' Following	6	
39		2' Following	9	
41		2' Head	10	Movies

Table 10 presents predictions of prototype resistance, EHP, (effective horsepower), trim and CG heave in smooth water, both at the designed static trim and at zero static trim. It is evident that in the maximum operating range of 7 to 9 knots, the effect of trim on resistance is minimal. Figure 20 is a chart of EHP vs speed at the designed trim. The prominent hump at 7-8 knots ($v/\sqrt{L}$ = 1.12 - 1.28) is characteristic of a hull of this fineness and proportions. The steep rise of EHP eases at 10 knots as flow starts to separate at the transom; above 11 knots the flow is fully separated. Because of the plane inboard faces of the two hulls, wave formation between the hulls is minimal.

Two test runs were made with the port belt running at about the same linear speed as the model towing speed in smooth water. A model drag increment of about 16 percent was recorded, due in part to interaction between belt and water, and in part to the effect of lowering the stern rollers for proper belt operation.

Table 11 presents predictions of prototype performance in head seas having a significant height of 2 ft. EHP predictions in waves have been added to the smooth water results in Figure 20.

Head sea tests at skimming speeds resulted in excessive pounding of the center section on wave crests. To reduce this undesired pounding, the center section was tilted about a stern axis to raise the center section bow by about 2 ft full-scale with respect to the hulls. By raising the centerbody structure as shown in Figure 18, a significant saving in EHP in waves was obtained due to a reduction in intensity of wave impacts against the centerbody bow.

Runs at forward speed in following seas and at zero speed in 4 ft significant height seas furnished qualitative assessments of performance. Runs at 6, 7 and 9 knots in 2 ft seas showed that motions were easy, no water was shipped over the transom, and the waves overtaking the vessel probably resulted in an EHP either the same as or less than EHP in smooth water. Behavior at zero speed in 4 ft seas showed that the craft was able to ride these waves safely.

TABLE 10

PROTOTYPE PERFORMANCE IN SMOOTH WATER

Δ = 50,090 lb

Run	Speed knots	Resistance lb	EHP	Trim deg	Heave of CG ft
Trim 0.8 ft by Stern (1.49°)					
7	4.01	214	2.6	1.50	-.06
8	6.00	585	10.8	1.49	-.16
10	7.01	1228	26.4	1.56	-.22
11	7.01	1218	26.2	1.59	-.22
9	8.01	1587	39.0	1.68	-.29
12	8.01	1572	38.7	1.70	-.29
13	9.02	2505	69.4	2.89	-.44
14	10.01	4537	139.5	4.71	-.56
15	11.01	5630	190.4	5.94	-.58
40	12.01	5946	219.4	*	*
Zero Trim					
16	7.01	1148	24.7	0	-.20
17	8.01	1555	38.3	-.15	-.27
18	9.02	2518	69.7	.95	-.45

1. Resistance and EHP are for salt water at 59°F based on the 1947 ATTC model-ship correlation coefficients (Schoenherr) with an addition of .0002 for surface roughness of clean hull.

2. Heave is vertical displacement of CG from its at-rest location; (-) indicates downward heave.

3. Trim is angular displacement of baseline from the horizontal (-) indicates bow down trim.

* No Data

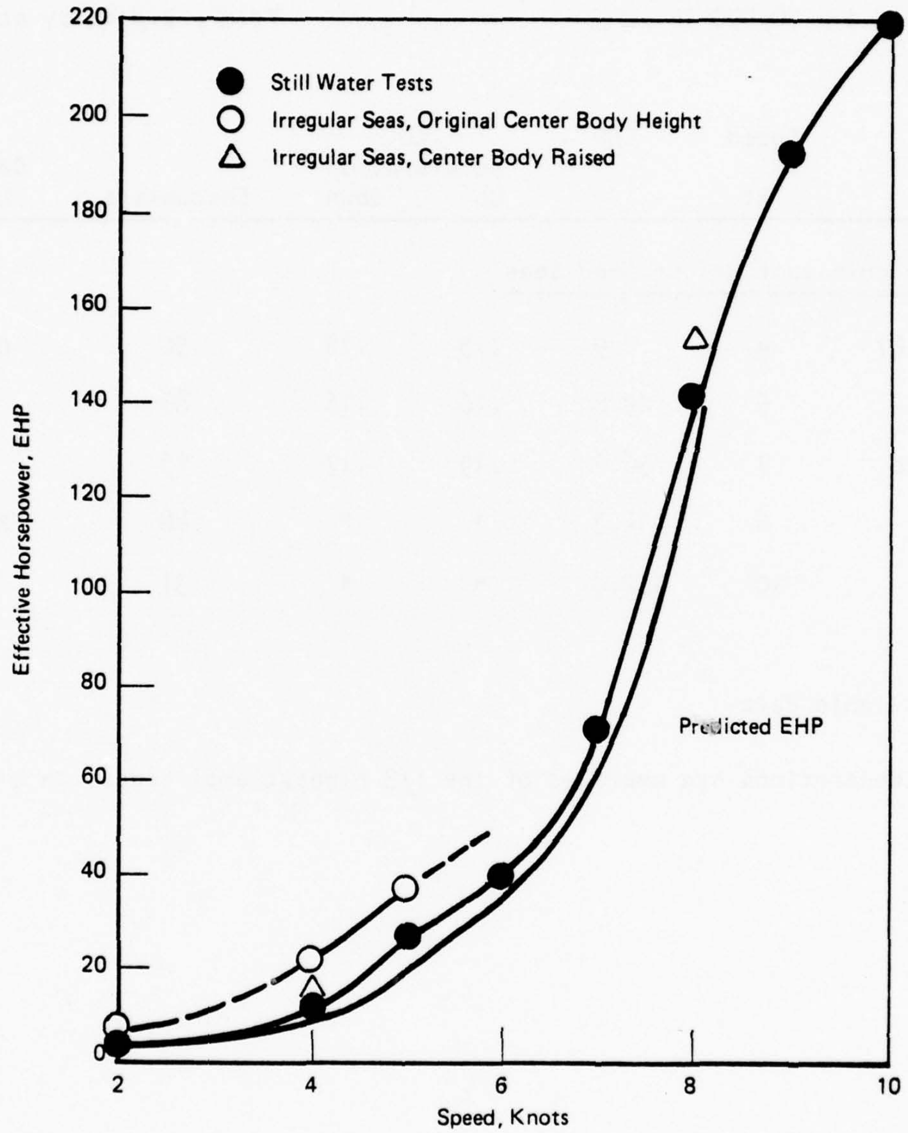

Figure 20. Resistance in Still Water and 2-ft Significant Seas
ZRV Power Curves

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TABLE 11

PROTOTYPE PERFORMANCE IN ROUGH WATER

Δ = 50,090 lb Trim = 0.8 ft by stern

Run	Speed kt	EHP	CG Acceleration Up	CG Acceleration Down	Encounters	Centerbody Location
2 ft Significant Height Head Seas						
22 or 27	4	6.9	.15	.14	50	Original
23 + 24	6	20.6	.16	.16	86	↓
25 + 26	7	36.3	.19	.17	73	↓
37	6	14.3	*	*	48	Raised
41	10	152.0	*	*	31	↓

*Unreliable data

CG accelerations are averages of the 1/3 highest amplitudes, in g's.

Discussion of Test Results

Resistance. Prior to the tests, an estimate of resistance of the vessel was made from data available in the naval architecture literature. This resistance curve (Figure 20) is based primarily on round-bilged trawler models modified by catamaran interference data. The resistance of the ZRV skimmer with its simplified V-bottomed hull was expected to be slightly higher than predicted, and as shown in Figure 20 it was for both smooth water and 2 ft significant head seas. Note that the characteristics of the measured resistance curve are identical with the prediction, including the hump at 7-1/2 knots. The location of this hump is a consequence of the pontoon, length limited to 41 ft by the space available in the C-130 cargo aircraft used for transport. If the skimmer were not designed for air-transportability, performance could be improved by slightly lengthening the pontoons to move the resistance peak out of the operating range. During the tests the water under the transom did not flow clear until a speed of about 10 knots was reached. At this speed, the resistance of the skimmer is nearly identical, percentagewise, with a trawler resistance. At lower speeds, the percentage resistance increase is greater. This indicates the need for reduced transom imersion.

Also shown in Figure 20 are the measured resistance values in 2 ft head seas with the center section as originally designed and with it raised at the bow. The reduction in wave resistance with the greater clearance is significant. Since it indicates that smoother water conditions will be achieved with this change, the skimming performance should be improved.

Oil Encounter Area. The space between the pontoons where the belts will pick up spilled oil was observed carefully during the towing tests to detect wave action. As expected, this area has a minimum of disturbance due to the pontoons, with only a slight frictional wake noticed along the inner sides of the pontoons and a shallow fore and aft displacement wave extending across the space. It is evident that at speeds up to 8, possibly 9, knots, the belts would be operating in relatively undisturbed water and should be fully effective.

Zero Speed Tests. The purpose of the zero speed tests was to observe the behavior of the skimmer in waves from various directions. Motions were found to be typical of a catamaran; low amplitude but rather jerky

motions in beam seas. Freeboard was entirely satisfactory in seas from all directions, and the skimmer should be perfectly safe and operable even in very steep seas of 4 ft significant height. Higher seas should not pose any problem since wave lengths will be longer, permitting the skimmer to ride up and over the waves.

Towing Tests in Waves. With the original center section height, the skimmer impacted frequently and tended to ride over head seas. With the center section raised 2 ft at the bow, impacting was greatly reduced and the skimmer tended to ride more nearly level. As a consequence, only an occasional wave crest washed over the bow of the pontoons, and this condition can be minimized by slightly increasing the prototype freeboard.

In following seas the skimmer rode very easily since the design waves resulted in a very small difference between wave speed and model speed. The resistance measured was actually lower than in still water, indicating benefit from "surfing". It is evident that skimming operations would be very effective in following seas. Freeboard aft was found to be more than adequate with no water evident on deck.

Belt Operation. Driven belts were modeled primarily to determine if important interactions--drag and wave effects--existed between the belt and water.

One could easily expect problems in trying to model at 1/8 scale the belt and drive mechanism properties such as bending stiffness and the consequent dynamics. (The belt operation was later modeled at full scale during the mock-up tests, see Chapters IV and V, and found to be satisfactory.)

Initially a great deal of difficulty was experienced in operating the loosely tensioned skimmer belts. Slipping and jamming was corrected by adding simple guide plates just ahead of each roller. Towing tests with the belts were limited to two runs running at near ZRV conditions. The belt speed was found non-consistant due to variations in drag, so the belt speed could be adjusted only to about ±10% of model speed.

Although results regarding the belt operation should be viewed as qualitative, belt-water interactions were generally found to be minimal at near-ZRV conditions and belt conformance satisfactory. Raising the center section containing the belts to reduce frontal wave impact not only reduced

resistance in waves but also seemed to improve skimmer belt operations by allowing the belt to follow the wave contour more naturally.

Prototype Design Changes

Based on a thorough evaluation of the model test results certain design changes were made in the prototype to enhance overall performance. These changes were:

1. The forward end of the center section (for about one-third of its length) was swept up about 2 ft higher than the original bottom contour. The bow roller was similarly elevated to provide greater wave clearance. Since there was no evidence of wave impact beyond the forward third of length, the after portion of the center section remains unchanged.
2. The deck line of the pontoons was raised (forward) about a foot to increase deck dryness in head seas. Freeboard at the stern (found to be more than adequate for all conditions) was slightly reduced to partially compensate for the extra weight of the greater depth forward. Consequently, the deck line of the pontoons is a straight line from bow to stern but with a slope instead of being level. In connection with the increased freeboard, the beam at the pontoon decks forward was increased slightly by carrying out the flare of the sides to a greater height.
3. Lines of the pontoon at the stern were slightly altered to reduce transom immersion. This reduces the buoyancy aft slightly and approximately compensates for the shift of pontoon weight forward resulting from the change in deck line.

VIII. MATHEMATICAL ANALYSES OF ZRV SKIMMING PROCESS

Introduction

The ZRV skimming process involves operating a composite, closed-loop sorbent belt to contact the oil on water, sorb quantities of oil and water, withdraw the mixture by withdrawing the belt, and expel the mixture from the belt by wiping and wringing. Because total wring-out of the recovered fluid is impractical, a residual volume of oil, say 30 to 40% of the maximum belt capacity, remains in the belt after multiple wringing cycles. This means that the mixture recovered during skimming is the total volume approaching the wringer minus that which is unrecoverable.

The fundamental part of the ZRV skimming process is that velocity differences between the belt contacting the oil layer on water and the water itself are minimized--a zero-relative-velocity condition.

Physical principles involved in this complex process are:

1. The sorbent belt has a fixed volume of voids which can be filled with oil.
2. The driving forces pushing oil into and through the sorbent, associated resistive forces, and modifying parameters are:
   a) Surface tension and capillary pressure
   b) Belt permeability
   c) Oil viscosity and density
   d) Skimmer geometry
   e) Operating conditions

Belt Sorption and Withdrawal

Using the above physical mechanisms an effective slick thickness of the oil picked up can be calculated from equations derived in Appendix C of the Stage I Final Report[1] to model belt contact and withdrawal. A digital computer program of the belt sorption and withdrawal model was developed and results are presented in Appendix C. This program has been used in part to make design decisions regarding both the mock-up and the prototype. Further, it has been used in part to resolve anomolies that surfaced during the mock-up performance tests.

Belt Wringing Model

Finally, the wringing process, not modeled previously, has been studied in order to predict pore pressures in the belt and pore-pressure related wringer horsepower requirements. A model by Skrabak[3] was adapted to describe the ZRV wringing process. It relates pore pressure in a compressible porous medium to geometry, oil type and other system parameters. Another digital computer program was written for this model.

The mock-up wringer is a vertically opposed pair of steel conveyors which resemble tank treads. The gap between conveyors converges exponentially over a five-foot length so that wringing is relatively gradual. The compression speed c of a segment of the sorbent belt is given by

$$c = V_B \, g_w{}'$$

where V_B is belt speed and $g_w{}'$ is the slope of the wringer's exponential gap curve. Typical wringer gap dimensions are 1.2" at the opening and 0.375" at the end of the wringer. Fitting an exponential curve to these dimensions gives the curve g_w as

$$g_w(x) = 1.2 \exp\left[-0.233\text{ft}^{-1} x\right] \text{ inches}$$

where $g_w(x)$ is in inches and x is the distance in feet along the wringer.

Over a range of compression ratios, the felt component of the belt occupies a nearly constant fraction of the gap width. In fact based on a simple lab test with a single Astroturf backing, the felt occupied 2/3 of the gap width. Static permeability tests described in Appendix E show that the permeability of the felt varies almost linearly with compression ratios, λ, between 0.5 and 1.0 as indicated in Figure 21. The permeability of the EX-1017 felt was approximated by

$$10^5 \, k = 2.79 \, \lambda - 1.17$$

3. Skrabak, M., "Mechanics of Pressing Wet, Porous, and Compressible Media", Verahrenstechnik, Vol. 7, No. 1, pp. 14-22, 1973.

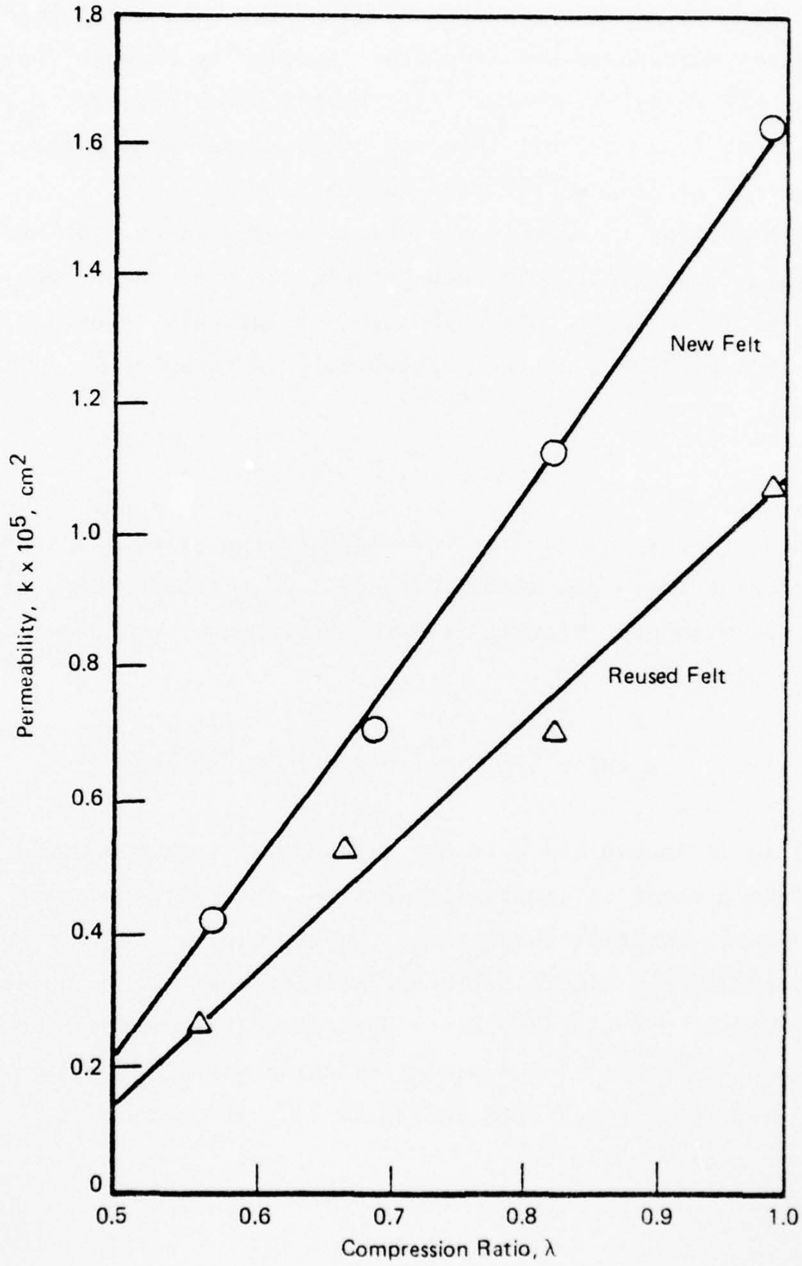

Figure 21. Variation in Permeability with Compression - Polypropylene Felt

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where k is the permeability in cm^2, and λ is the ratio of the felt thickness to its original thickness.

Values of the dynamic pore pressure can be bracketed by two calculations. The lower bound is found by using the uncompressed permeability ($\lambda = 1$). The upper bound is found by using a permeability corresponding to the instantaneous compression of the felt. These two calculations were performed using Skrabak's analysis[2] (see Appendix F). The results, plotted in Figure 22 show bounds on the maximum pressure drop across the felt. The lower bound, calculated with constant material properties, actually drops with increasing compression. This is because the compression speed drops as the belt progresses through the wringer. Pressure is constant in the first two feet of the wringer since only Astroturf is squeezed there. Since relatively low pressures are required to compress Astroturf, it was not modeled in the mathematical analysis. Recalling wringer simulator results from Stage I work, it can be seen that most of the fluid is driven out at high values of permeability. The advantage of using an exponentially decreasing wringer gap is that this shape lowers pore pressures from what they would be in a linearly decreasing wringer.

A special experiment was set up to provide confirmation of the wringing model. In order to avoid measurement problems that might confuse the comparison, the experiment described in Appendix G was conducted using two half-inch layers of EX 1017 felt and no Astroturf. The conditions for this comparison were straightforward so the computer model could be readily checked.

Results of the comparison between experiment and theory were good. The math model successfully bracketed the experimental results, as described also in Appendix G.

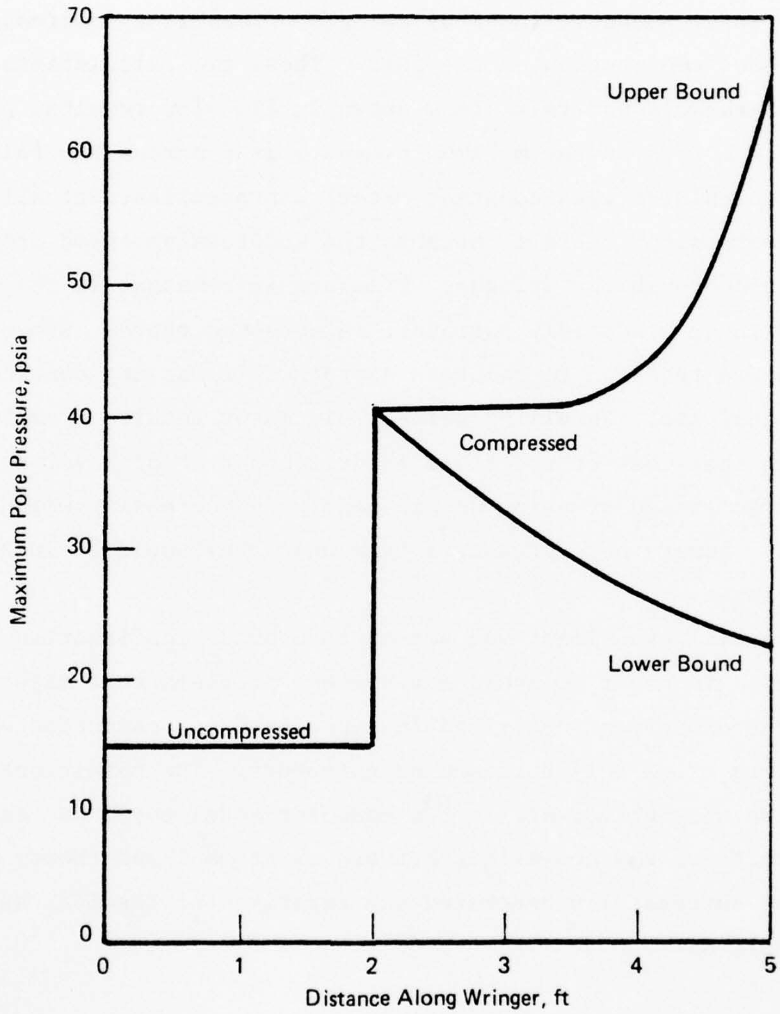

Figure 22. Dynamic Wringing Pressures

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IX. OTHER TESTS AND ANALYSES

Sorbent Belt Tests

Several series of tests were performed on samples of belt materials and small sections of composite belt to determine properties affecting the prototype design. The conclusions drawn from these tests are shown in Table 12.

Chemical and mechanical degradation tests were performed on specimens of Astroturf, EX 1017 Polypropylene felt, and composite belt sections. Samples of Astroturf and felt were soaked in distilled water, sea water, or various oils for many days, then were subjected to tensile tests to determine the effect of prolonged contact with these liquids. Small composite belt coupons (one layer of felt sandwiched between two layers of Astroturf) were compressed and released in an oil bath for 1800 cycles. Tensile tests determined the amount of mechanical degradation. Stress/strain curves show a considerable amount of creep and hysterisis in the loading/unloading cycle.

Another test used a paired-roller wringer apparatus to study belt life and degradation of three sections of belt, each constructed in a different manner. Belt constructions are shown in Figure 23. The three sections were sewn into one continuous loop and cycled through the wringer and oil bath 60,000 times. After cycling, tensile tests determined the amount of mechanical degradation. Oil absorption studies made on felt (EX-1017) samples removed from the cycled belt showed an appreciable drop in sorption capacity. Comparison of the three methods of belt construction led to the successful design used in the mock-up.

In still another test series the amount of water absorbed by Astroturf fibers in prolonged contact with water was measured. To aid the mock-up design effort, comparative oil absorption and compressibility tests were run on EX 1017 and EX 745 felts.

The composite conclusions drawn from these tests are accounted for in the final belt design (see Figure 5).

TABLE 12

SORBENT BELT TESTS - CONCLUSIONS

Characteristics	Conclusions
A. **Belt (Astroturf) strength**[a]	More than adequate. 526#/in. width in unused condition.
B. **Belt (Astroturf) degradation by mechanical stressing in oil**	Adequate strength was retained. 453#/in. width after 60,000 cycles in No. 2 diesel oil. 400#/in. width after 1800 cycles in Navy oil.
C. **Belt (Astroturf) degradation by prolonged contact with water**	Little effect on strength in 42 days.
D. **Belt (Astroturf) degradation by prolonged contact with oil**	Little effect on strength in 42 days.
E. **Water absorption by astroturf**	Very little in 7 days.
F. **Oil absorption by polypropylene felt**	Unused EX 1017 and EX 745 have the same absorption capacity - 0.81 gm/cm^2. Cyclic stressing reduces absorption capacity of EX 1017 to 0.58 gm/cm^2 after 60,000 cycles. EX 745 was not cyclically stressed.
G. **Felt compressibility**	Approximately one-third as much force is required to obtain a given compression of EX 745 as compared to EX 1017.
H. **Belt life**	Adequate - little wear observed after 60,000 cycles of an Astroturf-EX 1017 belt (simulating 200 hours operation at a constant 6 knots).
I. **Belt construction**	Little difference was found, but two layers of Astroturf enclosing a single piece of felt with widely spaced longitudinal stitches seemed preferable. Belt tracking considerations indicate a symmetrical design should be used.

a. **Since felt has very low tensile strength, belt strength is determined entirely by the strength of the Astroturf covers.**

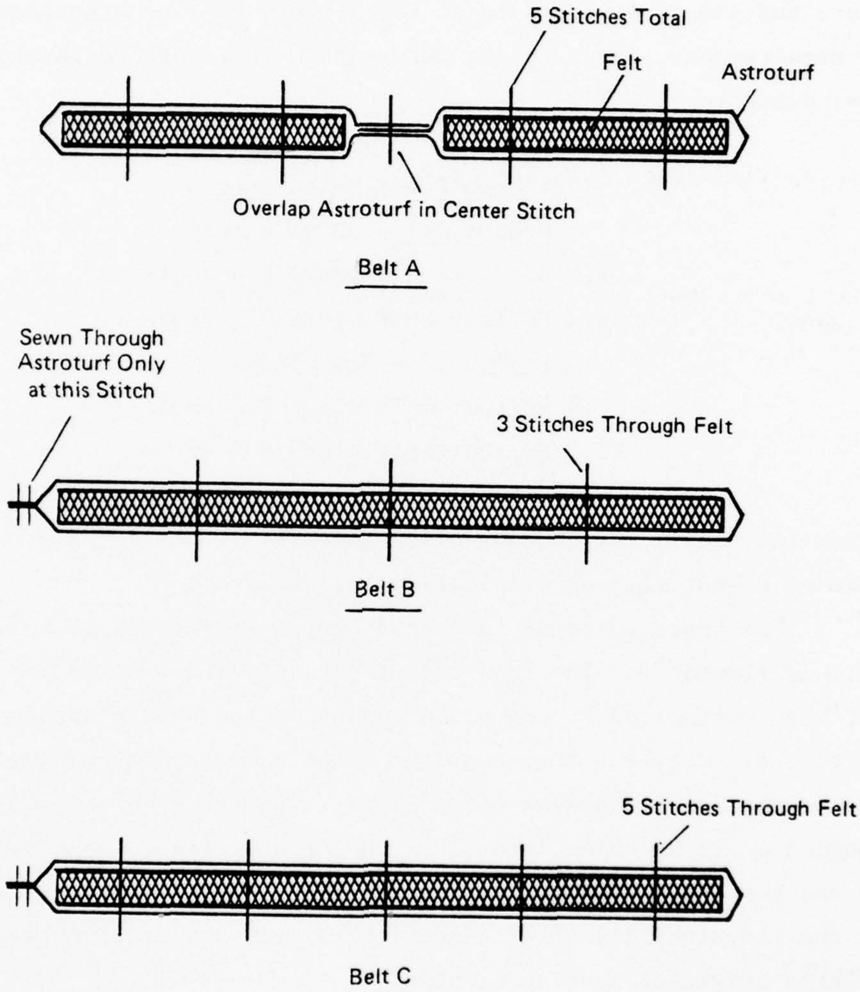

Figure 23. Test Belt Construction Schematic

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Wringer Power Measurement

A load cell was attached to the mock-up in Houston tests 28, 29, 34 and 35 to measure the power input to the wringer. Data obtained was used to estimate the power requirements of the prototype. The experimental wringer power requirements, shown below, were within the range estimated during the wringer design.

Wringer Power Measurements

Medium Oil - 10 mm slicks

8.1 HP/foot belt width @ 4 knots

14.2 HP/foot belt width @ 6 knots

Heavy Oil - 3mm slicks

7.4 HP/foot belt width @ 4 knots

13.9 HP/foot belt width @ 6 knots

Data was taken only for viscous oils since this represented a "worst case" because of higher viscous dissipation losses.

The test apparatus for horsepower measurements is shown schematically in Figure 24. The load cell indirectly measured the chain tension which, when multiplied by the pitch radius of the driven sprocket, gave the input torque. Only the torque on the upper conveyor was measured; input torque to the lower conveyor was assumed to be the same. Power input from the engine could be calculated since the wringer speed was known. The apparatus was completely dismantled and recalibrated between Tests 29 and 34 to check the repeatability of the data. Load cell calibrations were made using an Instron universal testing machine.

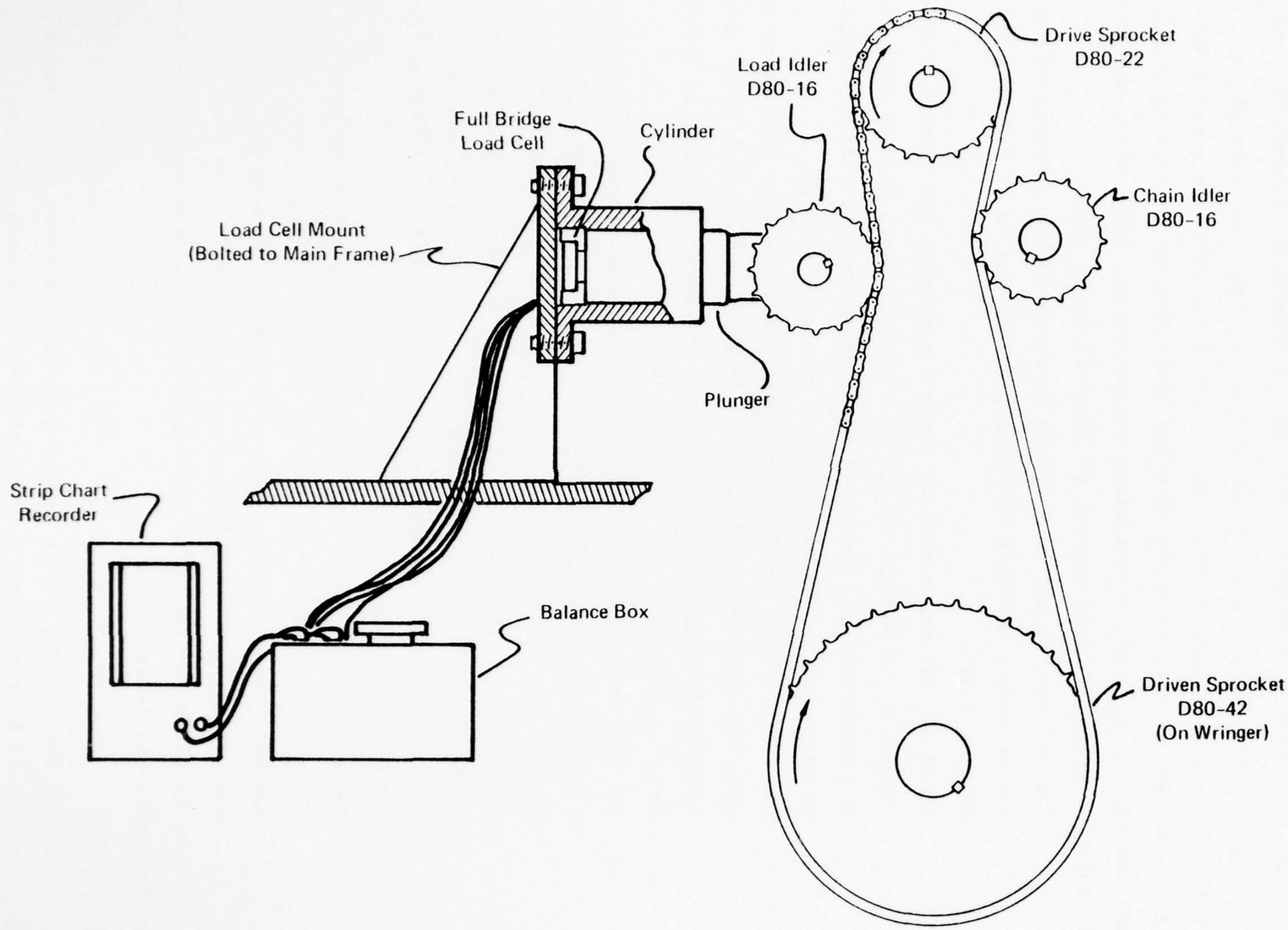

Figure 24. Power Measurement Apparatus

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X. CONCLUSIONS

The ZRV Skimmer development program has progressed through two stages -- concept feasibility and full scale mock-up testing. The concept is a means for high speed skimming in which oil is collected from the water's surface at a condition of zero relative velocity (ZRV) between a floating sorbent belt and the oil layer. Major conclusions concerning the ZRV concept and projected prototype performance at the end of Stage II tests are:

1. The ZRV concept has been proven by tests to be extremely effective at (water relative to vessel) velocities up to 8 knots, the testing limit.
2. Based on full scale mock-up tests a prototype ZRV Skimmer should collect up to 600 gpm of oil at 6 knots. Tests further show that in thinner slicks, less than 5 mm, approximately 95% of the oil encountered will be recovered at speeds to 8 knots.
3. The 40-foot-long aluminum catamaran vessel design, with skimming apparatus between hulls, was confirmed by model tests to be safe, stable and suitable for skimming at speeds to 10 knots in inshore waves to 2 feet.
4. The most difficult design-related problem was found in developing a lightweight, compact, efficient and economical high-speed belt wringer for the prototype. An effective wringer was designed and built for the mock-up tests, but there was no major weight constraint. The prototype wringer, designed during this stage, is of greatest concern regarding reliability because of its unusual and complex features.
5. The prototype sorbent belt made from two layers of Astroturf (outer surfaces) and one Fuetron felt layer (inner core), should exhibit good belt life characteristics, since only one belt was used during the entire mock-up test program.

More detailed findings from mock-up and model tests, already incorporated in the prototype design are:

Vessel

1. The forward end of the center (skimming) section of the vessel should be raised two feet to minimize head seas slamming.
2. The freeboard of the pontoons forward should be raised about one

foot to increase deck dryness.

3. The lines of the pontoon at the stern should be altered to reduce transom immersion.

Wringer

1. A different design should be used in which the squeeze plates do not separate in turns at the conveyor ends.
2. Wringer plates should be designed so as to minimize warpage in fabrication.
3. A network should be provided to lubricate the squeeze plate support bearings.
4. Machined structures should be used to support the plate support bearings so that closer wringer gap tolerances are possible.
5. A more reliable method of tensioning the wringer conveyors should be used than screw-type take-ups.
6. The wringer should be designed so as to prevent oil spray from re-wetting the belt.

Sorbent Belts

1. Sorbent belts should be made of one layer of EX 745 polypropylene felt sewn inside two layers of Astroturf.
2. Conventional alligator belt lacing should be used to join the belt ends.
3. It may be beneficial to sew some closed-cell polyurethane foam strips into the longitudinal seams of the belts for added buoyancy in waves.

Belt Tracking

1. Rollers should be aligned very carefully
2. Crowned rollers are not necessary.
3. Ends of rollers should be flanged where practical.
4. Surface-piercing belt guides (other than the hulls) should be avoided.

Belt Tensioning

1. An easy method of taking up belt slack must be provided.
2. A means of controlling belt tension on the water must be provided.

Power

1. Approximately 14 HP/foot of belt width must be provided to drive the wringer at 6 knots.
2. Approximately 3 HP/foot of belt width must be provided to drive the front rollers at 6 knots.

AD-A041 416 SHELL DEVELOPMENT CO HOUSTON TEX F/G 13/2
A ZERO-RELATIVE-VELOCITY BELT SKIMMER, STAGE II - CONFIRMING TE--ETC(U)
MAY 77 R R AYERS, J M WARD DOT-CG-42229-A
UNCLASSIFIED USCG-D-23-77 NL

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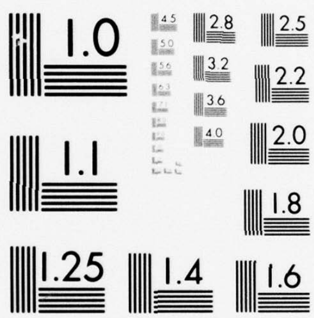
1.0
1.1
1.25
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1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0
4.5
5.0
5.6

XI. RECOMMENDATIONS

1. A prototype ZRV Skimmer should be built and tested. Results of the Stage II program show that this skimmer should be highly effective in recovering spilled oil from rivers, bays, and harbors at speeds to 8 knots.

2. A design and test program should be conducted to develop a simpler, lighter and less expensive wringer mechanism which would work as efficiently as the present design. Comparative testing of wringer mock-ups could be used to prove and refine a new design.

APPENDIX A

USCG DESIGN GOALS

TABLE A-1

FAST CURRENT OIL RECOVERY
DESIGN GOALS

Areas of Operation

a. Bays, Harbors, Estuaries
b. Coastal Rivers
c. Coastal Waters

Operational Environment

Up to 10 knots current with optional recovery in the 6 to 7 knot range and 2 foot confused seas with 20 knot winds.

Survival Environment

With Current

a. 15 knots current with calm sea
b. 10 knot current with 4 foot waves and 20 knot winds

Moored or Adrift

a. 6 foot wave height with 40 knot wind for one week

Minimum Oil Thickness

0.04"

Oil Type

Complete range of oils including distillate fuel oils, residual fuel, and crude oil with optimum recovery to be in the range of 10 cs to 500 cs.

Sea Temperature

+28°F to 100°F

Air Temperature

0°F to 120°F

Mode of Operation

Moored, towed and self-propelled

Transport from Central Storage to Nearest Port

One C-141 or two C-130's (two modules of 39' x 9' x 7' 10" LWH with a maximum weight of 25,000 pounds each)

Transport from Nearest Port to Scene

a. Self-Propelled
b. Towed by CG or commercial vessel equal to or greater then a CG 82 foot WPB
c. Carried on deck of CG 180 foot WLB or a comparable commercial vessel

Power Supply

Included

Fuel Supply

12 hour endurance

System Integrity

Impervious to the environment and oil.

Cleanability

Easy to clean

System Support

a. Simple to assemble, install, load, launch, tend, refuel, maintain, operate, repair, and retrieve
b. Reliable
c. Assembly to be accomplished on scene in two hours

Control Function

System shall be capable of controlling oil so that it can be recovered.

Recovery Function

a. Throughput Efficiency $\geq$ 95%
b. Recovery Efficiency $\geq$ 75%
c. Recovery Rate up to and including 1000 gpm

Debris Handling/Protection Function

Shall be able to handle a moderate size and amount of debris.

Pump and Transfer Function

Pump up to 1000 gpm and not emulsify the oil.

Temporary Storage

Temporarily store 2000 gallons aboard and 500 long tons by external means.

APPENDIX B

MOCK-UP TEST DATA-HOUSTON

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TABLE B-1

SUMMARY OF TEST COMMENTS AND DESIGN CONCLUSIONS - HOUSTON TESTS

Runs	Comments and Conclusions
1 - 6	Checked out equipment; realized oil distribution was a potentially serious problem at high speeds. Abandoned oil distribution with close nozzles.
7 & 8	Tried testing in free floating slicks. Results were promising.
9 & 10	Tested in free-floating slicks made by sectioning the test area into 50-foot lengths with booms, applying known volumes of oil to the sections, then removing the booms to obtain a fairly uniform slick. Made modifications to collect front sample and prevent rewetting the belt with spray from the wringer area. Test results indicated that all further tests should be made in free-floating slicks.
11 - 14	Discovered that proper belt tension (less slack in belt) reduced spray off rear drum and significantly improved performance.
15 - 21	Realized that all surface piercing objects near the belt cause undesireable turbulence and must be removed or their effects minimized if possible. The new felt (EX 745) may have a hard time holding on to oil at 8 knots because of its low density. The original felt used in Stage I was denser but required higher wringer forces and consequently more power.
22	Loose conveyor chain in the wringer caused several squeezing plates to break. A major repair effort resulted. The following lessons were learned: 1) Conveyor chain carrying the squeezing plates must be tight and under control at all times. 2) A lubricant system must be provided for all bearings. 3) Closer tolerances must be maintained in wringer construction. The lower unit was badly misaligned in fabrication and this was not discovered until the breakdown in Run 22.
23 - 39	Viable data was obtained and no major changes were made.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE (GPM)	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIFNCY (%)	COMMENTS
5/11	1 (L)	4	4	3	49	31	82	Checked out mechanical equipment and test procedures; had problems with aluminum flap on the oil nozzle.
5/12	2 (L)	4	4	3	61	44	102	Apparently the aluminum flap worked O.K.
5/12	3 (L)	4	4	10	108	72	– T.C.* 5.4	Aluminum flap was pushed under water by nozzle forces.
5/13	4 (L)	6	6	3	55	40	57	Checked material balance: oil distributed, 48 gal; oil collected, 27.3 gal; oil left behind, 25.3 gal; 4.6 gal. error = 10%.
5/14	5 (L)	6	6	3	48	38	53	Moved oil distribution nozzle to front of tow truck; the aluminum flap failed and oil was pushed under the surface.
5/15	6 (L)	6	6	3	69	51	76	The oil nozzle remained in front of the truck apprx. 35 ft ahead of initial belt contact. A longer, sturdier flap was used. Actual run speed was 6.5 knots. Runs 3-6 indicate that the oil distribution nozzle will not work for thick slicks or high speeds.

**T.C. Thickness collected in millimeters. Throughput efficiency is an inappropriate term when the slick thickness exceeds the belt sorption capacity. T.C. gives capacity under test conditions.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THNKS (MM)	OIL RECOVERY RATE (GPM)	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
5/15	7 (L)	6	6	4.7 estimate	115	82	87 estimate	The oil nozzle was abandoned. The skimmer approached a free-floating slick of undetermined thickness. Slick thickness was estimated from thief measurements
5/15	8 (L)	6	6	3.3 est.	73	61	79 est.	Wringer gap was adjusted slightly before the run. The skimmer went through another free-floating slick. Slick thickness was estimated by thief measurements.
5/17	9 (L)	6	6	10	83	60	- T.C. 2.8	This was the first 10mm run using foam logs to separate the 300-ft test length into 50-ft segments. 35 gal. of oil were poured into ea. segment. Foam logs were removed just prior to run. A strong north wind piled the oil up against the logs. A
								tremendous "rooster tail" appeared in the skimmer wake.
5/21	10 (L)	6	6	10	142	60	- T.C. 4.8	Between runs 9 & 10 many changes were made to reduce rewetting of the belt in the wringer area. Front sample pans, trays, shields, and wipers were added. Run 10 checked out these changes. Again a lot of spray was noticed in the rear area.
5/24	11	6	6	no oil	-	-	-	The canal water level was about 2 inches lower than in previous runs. No "rooster tail" was seen.

DATE	TEST NO (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE (GPM)	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
5/24	12 (L)	6	6	10	140	85	- T.C. 4.8	The canal level was low again. (same as run 11). No "rooster tail" as in runs 9 & 10 seen. The belt was slack after exiting the wringer and fairly taut on the water. Apparently the forward rollers were not pulling hard enough.
5/25	13	6	6	no oil	-	-	-	The water level was raised to the level of runs 9 & 10 to determine if belt tension or canal water level caused the improvement in oil/total ratio in run 12. No rooster tail appeared and the belt was tight on the water.
5/25	14 (L)	4	4	10	104	81	- T.C. 5.3	Runs 11-13 showed that belt tension was important. A pneumatically tensioned belt idler was added to keep the belt tight on the water. It worked well.
5/26	15 (L)	8	8	10	91	50	- T.C 2.3	Wind blowing from the south at 10 mph pushed the oil up against the barriers. The "rooster tail" contained fine black oil droplets. Low oil recovery was a concern.
5/27	16 (L)	8	8	10	98	58	T.C. 2.5	A calm wind allowed a fairly even slick. Belt guides created a large turbulent bow wave directly in front of the belt contact point. Again low oil recovery was a concern.
5/27	17	8	8	no oil	-	-	-	This test was made to see what caused the turbulence. Belt guides were the main cause of turbulence with the guide rollers helping out.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE (GPM)	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
5/28	18	8	8	no oil	-	-	-	The canal level was lowered so that the belt guides and guide rollers were always out of the water. The water ahead of the belt contact point was smooth this time.
5/28	19 (L)	8	8	10	96	62	- T.C. 2.4	Before this run the guide rollers were raised 1" & the belt guides were cut back so that they extended only as far forward as the belt entry point. The water level was raised up to the level of run 11. Guide roller nuts still cut water causing spray.
6/1	20	8	8	no oil	-	-	-	Guide rollers were raised another inch then checked to see if they still cut water. Further changes were needed. Front guide rollers were raised and rear rollers moved behind the skimmer. All but the
								last 8-foot section of belt guides were removed.
6/4	21 (L)	8	8	10	104	84	- T.C. 2.6	Water was smooth in front of the belt. A dark black rooster tail of fine droplets was seen coming off the rear drum. After the run we found the wringer gap to be questionable. It was adjusted to 0.333" by measuring the outside of the plates.
6/7	22	8	8	10	95	87	- T.C. 2.4	This run was to check the effect of the wringer adjustment. A fine black rooster tail was apparent again. Three of the perforated wringer plates broke at the beginning of the run. This was not realized

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE (GPM)	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
6/7	22 (cont.)							until after the run was over. The belt was not damaged. During the repair the wringer was realigned and the gap was set very carefully to 0.333" with the belt removed. A second truck was fitted with a Marlow double diaphragm pump, 550 gal oil supply tank, and the oil nozzle used previously.
6/15	23 (L)	4	4	2.9	57	38	98	The test procedure for this and for all subsequent tests was changed so that a separate truck spread oil on the canal about one minute before the skimmer ran through it. In this run everything worked
								well and the water behind the skimmer was clear of oil.
6/15	24 (L)	6	6	3	91	45	105	A prominent rooster tail of clear water about 3 ft. high was seen. No problems were encountered during the run.
6/16	25 (L)	6	5.5	3	99	52	115	At the start of the run the wringer ladder hit a bucket. The noise startled the operator so he blew the emergency stop signal. Quickly realizing there was no danger the run resumed normally.
6/16	26 (L)	6	6	10	170	85	- T.C 5.7	The run went normally. A medium-sized black rooster tail was visible.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE (GPM)	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
6/16	27 (L)	6	5.5	10	174	93	- T.C. 5.8	Same as run 26
6/21	28 (H)	4	4	3.5	61	61	91	700 cs oil. Normal run. The slick was somewhat patchy. A simple test showed equilibrium thickness to be 4.3 mm. Load cell measurements were made to determing wringer power requirements.
6/22	29 (H)	6	6	3	91	72	101	850 cs. oil. Normal run. Patchy slick. Load cell readings were taken.
6/23	30 (H)	4	4	10	155	82	- T.C. 8.0	900 cs. oil viscosity.
6/23	31 (H)	6	6	10	148	88	- T.C. 4.9	550 cs. oil viscosity. A small black rooster tail was seen.
6/29	32 (M)	4	4	3	65	54	110	140 cs. oil viscosity. Actual speed was approx. 4.6 knots. The belt was wetted thoroughly with the medium oil before the run.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE (GPM)	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
6/30	33 (M)	6	6	3	90	65	100	150 cs. oil viscosity. An attempt was made to get a load cell reading but the meter went off scale.
6/30	34 (M)	4	4	10	141	91	- T.C. 7.1	110 cs. oil viscosity. Load cell readings taken.
6/30	35 (M)	6	6	10	152	87	- T.C. 5.1	102 cs. oil viscosity. Load cell readings taken.
7/1	36 (M)	6	5.5	3	92	68	103	150 cs. oil viscosity. Normal run
7/1	37 (M)	6	5.5	10	151	89	- T.C. 5.1	112 cs. oil viscosity. Normal run
7/1	38 (M)	6	6.5	10	160	91	- T.C. 5.3	102 cs. oil viscosity. Normal run.

DATE	TEST NO (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
7/2	39 (M)	6	6	3	82	66	91	140 cs. oil viscosity. Caught a small sample from the rear drum rooster tail; very little oil was found.

APPENDIX C

MOCK-UP PERFORMANCE TEST DATA-OHMSETT

TABLE C-1

TEST SERIES IDENTIFICATION - OHMSETT TESTS
(in order of testing)

Test Series	Oil	Description and Purpose
S	None calm and waves	Shakedown; check out equipment and test procedures; establish initial settings on device parameters.
12	Sun 1650 calm	Speed variation; find the optimum speed with initial devices parameters.
13	Sun 1650 calm	Slick thickness variation; check response to slick thickness variations at optimum speed found in series 12.
15	Sun 1650 calm	Device parameter variation; find optimum parameter settings (e.g., belt tension, drum height, relative velocity) at optimum speed found in series 12.
12-A	Sun 1650 calm	Speed variation; find new optimum speed at optimum parameter settings found in series 13.
19	Sun 1650 waves	Speed variation in 2-foot harbor chop; find optimum speed.
20	Sun 1650 waves	Thickness variation in harbor chop; check response to slick thickness variations at the optimum speed found in series 19.
22	Sun 1650 waves	Regular waves; check response in regular waves of varying lengths at optimum speed found in series 19.
4	Sun 7 calm	Device parameter variation; find optimum parameter setting at optimum speed found in series 12-A.
1	Sun 7 calm	Speed variation; find new optimum speed at optimum parameter settings found in series 4.
2	Sun 7 calm	Thickness variation; check response to slick thickness variations at optimum speed found in series 1.
8	Sun 7 waves	Speed variation in 2-foot harbor chop; find optimum speed.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
7/28	S-3 Sun 1650	4	4	3				Shakedown. Oil very sticky. Insufficient pre-wetting. Oil distribution guides used. Rear drum 9-1/2" high. Viscous oil - 900 cs.
7/28	S-3R Sun 1650	4	4	3				Front roller gap opened from 3/8" to apx. 1/2" before run. Conveyor-type rollers added before run to reduce viscous drag in guide tray. Diesel throttle broke during run. Oil distribution by-pass valve found open after run, should have been closed.
7/28	S-3S Sun 1650	4	4	3	52	70	91 E*	Oil distribution O.K. - 15" - 18" slick width. Belt covered entire slick - little oil behind.
7/28	S-4 Sun 1650	5	5	3	40	60	60 E	O.K. slick width 15"-18". From below, Ray saw oil on water then belt contracting and soaking up oil - little loss behind.
7/28	S- Sun 1650	6	6	3	35	47	41 E	O.K. slick width 12"-15". A lot of oil in large drops was churning under the belt as it passed. Control room data showed we were operating at zero rel. vel. Large losses.
7/29	S-6 Sun 1650	6	6	3	39.7	62	54 E	Dropped oil guide plates before run. Slick width 42"-48". Data based on 85% of oil dist. was encountered. Some turbulence below belt. Finer droplets than S-5. Clear water seen on top of belt just before rear drum.

*E - Percent of slick encountered estimated by observer on bridge.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
7/29	12-3 Sun 1650	6	6	3	54.2	68	74 E	75% of slick encountered (est.) Actual speed 5 knots. Some clear water on top of belt. No turbulence below belt this time.
7/29	12-2 Sun 1650	4	4	3	36	67	71 E	Encountered 67% of slick (est.) Pickup looked good.
7/29	12-1 Sun 1650	2	2	3	15	70	77 E	Encountered 67% of slick (est.) O.K. Belt entering water & soaking up oil visible through underwater windows. Ray noticed a large surge of oil out slop chutes as tilt tray went back at end of run.
7/29	12-5 Sun 1650	6	6	3	56	73	73 E	Looking for oil residence time in wringer. Oil builds up in tilt tray during run and is dumped out the slop chutes as tilt tray returns to slop position.
7/29	12-7 Sun 1650	4	4	3	66	54	123 E	New test procedure used - sample is started when skimmer first gets oil in wringer -at end of run wringer is disengaged. Tilt tray remains in sample position. Sample is allowed to drain into sample pan during return trip down tank. Test procedure fouled up this run.

DATE	TEST NO (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
7/29	12-7R Sun 1650	4	4	3	59	62	133 E	New procedure O.K. est. 70% of slick encountered.
7/29	12-4 Sun 1650	5	5	3	66	63	128 E	New procedure O.K. est. 70% of slick encountered.
7/29	12-8 Sun 1650	6	6	3	72	65	100 E	Run looked good from underwater windows. Ray and Jim observing. Est. 80% of slick encountered. Actual speed 5.75 knots.
7/29	13-2 Sun 1650	6	6	5	84	51	96 E	Rear sample pan failed to open. Est. 55% of slick encountered. Slick spread out 48" wide - not 5mm thick.
7/29	13-2R Sun 1650	6	6	5	97	77	71 E	Est. 85% of slick encountered. Distribution pump went down halfway through run. Oil guide ropes added to guide oil to skimmer.
7/30	12-3R Sun 1650	6	6	3	84	76	101 E	Est. 85% of slick encountered. Grid cross and camera installed before run to record slick width - worked O.K.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
7/30	HC-1	4	4					No oil - 2' harbor chop - belt responded well. Lots of water in rear drum area. Guide plates flexing too much.
7/30	15-2 Sun 1650	6	5.5	3	71	69	83 **S	Braided guide ropes used. About 85% of slick encountered.
7/30	15-2R Sun 1650	6	5.5	3	84	68	94 S	Guide ropes adjusted - missed about 2" of slick on right side. Belt speed not steady.
7/30	15-2S Sun 1650	6	5.5	3	80	68	90 S	Guide ropes adjusted - no change in results. No buildup or wave of oil in front of belt contact line.
7/30	15-3 Sun 1650	6	6.5	3				Wringer speed went up to 7.5 knots. Excessive vibration in wringer drive train. Operator immediately shut wringer down. No damage found.
7/30	15-3R Sun 1650	6	6.5	3	93	62	102 S	Oil not quite to surface as belt passed over. Some turbulence around guide ropes.

**S - Percent of slick encountered estimated from photographic slides taken during run.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
7/30	15-4 Sun 1650	6	5	3	86	68	93 S	More turbulence below belt than before. More loss behind.
7/30	15-5 Sun 1650	6	7	3	75	57	83 E	Could see belt more clearly from below than runs where belt was slow.
7/30	15-8 Sun 1650	6	6	3	95	60	109 E	Before run raised rear drum to 15 1/2" above water level. Skimmer running through about 30 ft. of oil before sampling.
7/30	15-9 Sun 1650	6	6	3	80	64	92 E	Raised rear drum to 15" above water before run. Moved ahead of oil at end of tank before running. Belt may have been too slack.
8/2	15-6	6	6	3	65	46	86 S	Tightened belt by moving out 1-3/4" on adjusting roller. Aux. bridge wheels broke near end of run slowing skimmer slightly before finish.
8/4	13-2S Sun 1650	6	6	5	110	79	80 S	The belt/water contact point was about 3 ft behind the tension roller.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/4	13-3 Sun 1650	6	6	8	123	86	123 S	Insufficient power in front rollers to keep belt slack. Only about 10' of belt contacted the surface Large losses visible. Belt still very wetted after going through the wringer.
8/4	12-1A Sun 1650	2	2	3	35	81	109 S	The belt stopped momentarily just as the skimmer received the oil. The bridge did not stop. The test resumed normally after about 10 sec.
8/4	12-2A Sun 1650	4	4	3	75	79	121 S	O.K.
8/4	12-3A Sun 1650	6	6	3	97	74	112 S	The front rollers not picking up slack. Belt contact far back at beginning of run but settled out later.
8/4	12-4A Sun 1650	5	5	3	89	75	119 S	The belt tensioned and slackened several times during the run causing a slapping on the surface. Some entrainment was noticed on underwater video during slapping.
8/4	19-1 Sun 1650	2	2	3	18	37	94 S	2 ft. harbor chop. Large amounts of water splashed on top of belt. Belt conformance was good. Visually, oil pickup looked the same as in calm water. Waves spread slick out more than in calm water tests.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/4	19-2 Sun 1650	4	4	3	38	26	71 E	2' harbor chop. Water on top of belt. Large amount of water spray coming out of wringer.
8/4	19-3 Sun 1650	5	5	3	48	25	139 S 83 E	2' harbor chop. Same as 19-2 .
8/4	19-4 Sun 1650	6	6	3	72	30	263 S 101 E	2' harbor chop. Same as 19-2 with more violent water sprays. Water shooting out of wringer.
8/4	20-2 Sun 1650	6	6	5				Slick spread out quite a lot - not 5mm thick.
8/5	22-1 Sun 1650	6	6	3	66	64	70 E	Regular waves. Much less water on top of belt than in harbor chop.
8/5	22-2 Sun 1650	6	6	3	66	60	91 S	Regular waves. The belt lifted at the entry as troughs passed then slapped down on the crests. Belt conformance aft was good. Small patches of oil were visible behind the skimmer coinciding with the slaps.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/5	22-3 Sun 1650	6	6	3	76	48	94 S	Regular waves. The wave was very long and small in height. Not apparent at all.
8/5	4-1 Sun 7	4	4	3	39	47	67 S	Sun 7 oil. Not all Sun 1650 oil worked out of Belt yet. Belt slack taken up 2" (4" total) before run. Oil distribution thicker on sides than at center.
8/5	4-2 Sun 7	6	6	3	30	38	39 S	Automatic stopwatch procedure used. Same oil distribution problem.
8/5	4-2R Sun 7	6	6	3	38	42	43 S	Corrected the oil distribution problem before run. Automatic stopwatch procedure used.
8/5	4-2S Sun 7	6	6	3	56	47	67 E	Reverted to the procedure used in viscous oil runs.
8/5	4-6 Sun 7	6	5.5	3	41	32	48 S	O.K.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/5	4-7 Sun 7	6	6.5	3	59	43	71 S	O.K.
8/5	4-8 Sun 7	6	5	3	66	51	90 S	More losses visible behind.
8/5	4-9 Sun 7	6	7	3	71	45	85 S	O.K.
8/5	4-5 Sun 7	6	6	3	51	35	58 S	Tightened belt 2" (4" total) Belt withdrawal angle less acute.
8/5	4-10 Sun 7	6	6.5	3	53	37	60 S	O.K.
8/6	4-5R Sun 7	6	6	3	65	48	80 S	The belt was oil-wetted well and this front roller gap was reduced somewhat before the run. There was a dip in the belt at the rear.

DATE	TEST NO (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/6	4-11 Sun 7	4	4	2	49	45	125 S	Excellent belt geometry. From underwater windows it was seen that oil soaked into the belt in the first 10 feet. Large droplets, 1-1/2 in.diam., were under the surface of the slick as the belt encountered it.
8/6	1-1 Sun 7	2	2	2	12	25	68 E	A thin slick encountered 1.5 mm. The water surface was very smooth behind the skimmer. From underwater windows it was seen that this oil was sorbed immediately on contact.
8/6	1-2 Sun 7	4	4	3	40	37	78 E	Similar to 4-11.
8/6	1-3 Sun 7	6	6	3	57	40	57 S	Belt withdrawal good, only a slight dip at the rear.
8/6	1-4 Sun 7	5	5	3	54	44	77 S	Belt withdrawal smooth - better than in 1-3. No dip apparent.
8/6	2-2 Sun 7	6	6	1	40	32	115 S	Very thin slick - almost invisible - no oil visible on tank behind skimmer. Belt Geometry was good.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/6	2-3 Sun 7	6	6	5	98	62	117 S	Belt geometry good - a slight dip at withdrawal.
8/6	2-4 Sun 7	6	6	8	124	69	127	Some oil spilled outside the guide ropes. There was some belt dip at the rear.
8/6	8-1 Sun 7	2	2	3				2 ft. harbor chop. Good wave conformance. Apparent loss behind skimmer.
8/6	8-2 Sun 7	4	4	3	30	15	96 E	2 ft. harbor chop. Good wave conformance with some belt slapping at the entry point.
8/7	8-3 Sun 7	5	5	3	47	18	189 E	Sample very emulsified. 2 ft. harbor chop.
8/7	8-4 Sun 7	6	6	3	50	16	200 E	2 ft. harbor chop Same as 8-3.

DATE	TEST NO (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/7	4-12 Sun 7	5	3	3	38	48	45 S	Wringer speed unsteady - varied Between 1 & 3 knots
8/7	4-12R Sun 7	5	3	3	60	50	83 S	A bow wave at the belt entry was plainly visible.
8/7	4-13 Sun 7	5	4	3	64	50	95 S	No bow wave. The belt entry was smooth with no apparent disturbances of the oil surface.
8/7	4-14 Sun 7	5	5	3	53	38	81 S	O.K.
8/7	4-15 Sun 7	5	6	3	39	40	82 S	Less dip at belt withdrawal.
8/7	4-16 Sun 7	5	7	3	48	36	71 S	Front rollers unable to keep up. The belt contact was about 10 ft. behind the ski. Belt exit was smooth with no wake.

DATE	TEST NO. (OIL TYPE)	TOW SPEED (KNOTS)	BELT SPEED (KNOTS)	DESIRED SLICK THKS (MM)	OIL RECOVERY RATE GPM	OIL/ /TOTAL REC. (%)	THROUGHPUT EFFICIENCY (%)	COMMENTS
8/7	11-1 Sun 7	6	6	3				Short regular wave
7/	23-2	6	6					No oil. A 6" x 6" x 5' wooden beam was towed ahead of the skimmer then released. The belt passed over it with no problems.

APPENDIX D

BELT SORPTION AND WITHDRAWAL COMPUTER PROGRAM

The mathematical model found in Appendix C of Reference 1 has been put in the form of a Fortram IV computer program. The governing flow chart is shown in Figure D-1.

Following in order are (1) a description of the computer program, (2) a listing, and (3) computer-calculated results in tabular output form which confirm hand calculated graphs in Figures C5, C6 and C7 of Appendix C to Reference 1.

Description of Computer Program

Several different calculations are necessary, depending on the oil properties and the skimmer operating conditions. These calculations apply to various combinations of saturated and unsaturated belt materials. The first part of the program, however, is common to all of the calculations. A data file is read in for the oil properties. The data file contains an integer flag in the first two columns, the oil's kinematic viscosity in the next 7 columns, and finally the oil's specific gravity in the last 5 columns. A sample data card is shown below.

```
+1+0.0460+0.84
```

Input Data

The terminal will then ask for a value of Ø, the ratio of residual oil volume to total void value. After the operator has typed in a value for Ø, the terminal will ask for a value for D_o, the slick thickness in centimeters.

The program is set up to generate curves like those shown in Figures C5, C6 and C7. Figure C5 is reproduced on page D-3. These give system behavior as a function of belt speed. Belt speed determines, t, the time available for the belt to absorb oil.

The first decision about further calculations is made when t_{hs} is computed. This is the saturation time for the felt. If t_{hs} is greater than t, the Astroturf is not saturated. Thus the felt absorbs no oil.

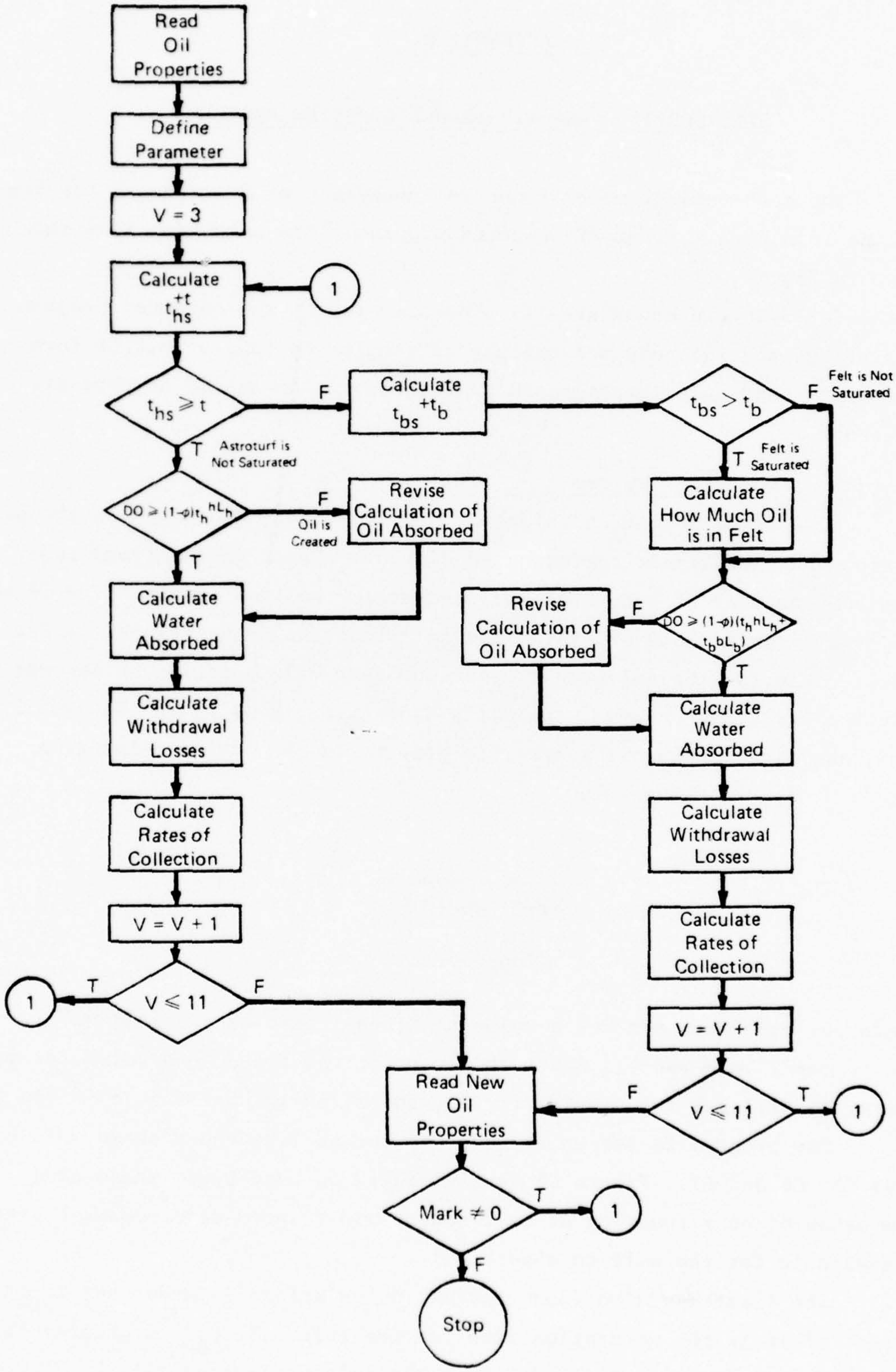

Figure D-1. Flowchart for Sorption and Withdrawal Program

0796

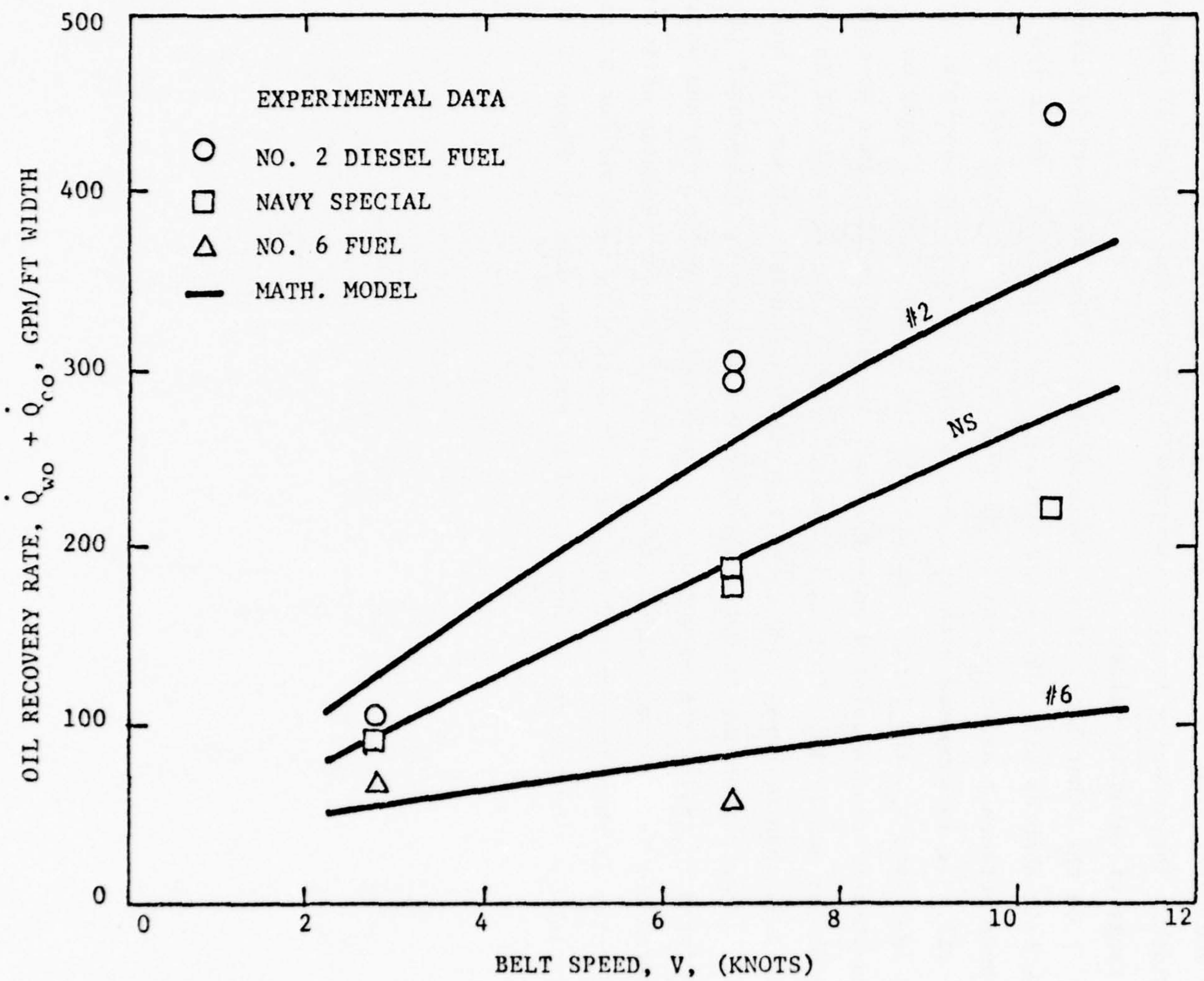

FIGURE C5 - TOTAL PREDICTED OIL RECOVERY RATE PER FOOT WIDTH BELT

OIL THICKNESS: 40 MM

BELT MATERIAL: FRESH

Nevertheless, it must be checked whether the thickness of the oil slick absorbed is less than D_o. If it is not, the calculation gives the result that more oil was picked up than is actually on the water. Hence it must be revised. Once a reasonable calculation of oil pick-up is accomplished, water absorbed and withdrawal losses are calculated. Finally the overall flow rate of oil and water from the wringer is calculated in units of gpm per foot of belt width. The velocity is then incremented and the calculation is repeated for a range of velocity values.

On the other hand, if t_{hs} is less than t, the Astroturf is saturated and the felt absorbs oil. Now a new time, t_b, is calculated. It is the difference between t and t_{hs}, and is the time available for the felt to absorb oil. It is compared with t_{bs}, the saturation time for the felt. If t_{bs} is less than t_b, the felt is saturated. In either case, it must be checked whether the calculated amount of oil absorbed is less than or equal to the amount available. That is if the calculated thickness of oil in the belt is less than or equal to D_o, the calculation stands. If not, it must be revised. Then the amount of water absorbed is calculated. Withdrawal losses are computed to revise the amount of oil collected. Finally, oil and water flow rated per foot of belt width are calculated, as is a skimming efficiency. The velocity is then incremented and the calculation is repeated for a range of velocities. The program is summarized in the flow chart in Figure D-1.

Program Listing - Belt Sorption and Withdrawal

```
      IMPLICIT REAL*8 (A-H,O-Z)                                         ZRV000
       DIMENSION  IFILOM (5)                                            ZRV000
      CALL RDOPEN(2,IFILOM,20,'INPUT',60,IRTN)                          ZRV000
      READ (2,2100) RM,ALP,S,R                                          ZRV000
      READ (2,2101) B,RKR,EPSH,RHOH,PH                                  ZRV000
      READ (2,2101) H,RKR,EPSH,RHOH,PH                                  ZRV000
 2100 FORMAT (F5.2,F6.3,F4.0,F5.2)                                      ZRV000
 2101 FORMAT (F4.1,E8.2,F6.3,F6.3,F7.0)                                 ZRV000
 2303 WRITE (6,2060)                                                    ZRV000
      WRITE (6,2060)                                                    ZRV001
      WRITE (6,2060)                                                    ZRV001
C     FEE IS RESIDUAL OIL VOLUME/VOID VOLUME                            ZRV001
      WRITE (6,834)                                                     ZRV001
  834 FORMAT ('   TYPE IN FEE, THE RESIDUAL OIL VOLUME/VOID VOLUME')    ZRV001
      READ (5,833) FEE                                                  ZRV001
  833 FORMAT (E12.5)                                                    ZRV001
      WRITE (6,2051) FEE                                                ZRV001
 2051 FORMAT ('  FEE=',E12.5)                                           ZRV001
      WRITE (6,2050)                                                    ZRV001
 2050 FORMAT (' THIS IS THE RATIO OF RESIDUAL OIL VOLUME TO VOID VOLUME'ZRV002
     1)                                                                 ZRV002
      WRITE (6,2052)                                                    ZRV002
 2052 FORMAT (' IF FEE=0,THE BELT MATERIAL IS FRESH')                   ZRV002
      WRITE (6,2053)                                                    ZRV002
 2053 FORMAT (' OTHERWISE ITS PRESOAKED AND PREWRUNG')                  ZRV002
      WRITE (6,831)                                                     ZRV002
  830 FORMAT (E12.5)                                                    ZRV002
  831 FORMAT ('    TYPE IN OIL SLICK THICKNESS')                        ZRV002
      READ (5,830) DO                                                   ZRV002
      WRITE (6,2054) DO                                                 ZRV003
C     DO IS SLICK WIDTH IN CM                                           ZRV003
 2054 FORMAT (' SLICK THICKNESS=',E12.5,'CENTIMETERS')                  ZRV003
      WRITE (6,2060)                                                    ZRV003
 2060 FORMAT ('     ')                                                  ZRV003
C     RNU=OIL VISCOSITY IN CM**2/SC                                     ZRV003
C     RHO=OIL DENSITY IN G/CM**3                                        ZRV003
  904 READ (2,903) MARK, RNU, RHO                                       ZRV003
      WRITE (6,2060)                                                    ZRV003
      WRITE (6,2060)                                                    ZRV003
  903 FORMAT (I2,F7.3,F5.2)                                             ZRV004
      IF (MARK .EQ. 1) WRITE (6,905)                                    ZRV004
      IF (MARK .EQ. 0) GO TO 2305                                       ZRV004
      IF (MARK .EQ. 2) WRITE (6,906)                                    ZRV004
      IF (MARK .EQ. 3) WRITE (6,907)                                    ZRV004
      IF (MARK .EQ. 4) WRITE (6,9907)                                   ZRV004
 9907 FORMAT (' A NEW OIL IS BEING CONSIDERED')                         ZRV004
  905 FORMAT (1H1,22X,'NO.2 DIESEL OIL')                                ZRV004
  906 FORMAT (1H1,21X,' NAVY SPECIAL OIL')                              ZRV004
  907 FORMAT (1H1,22X,'NO. 6 FUEL OIL')                                 ZRV004
      WRITE (6,2060)                                                    ZRV005
C     RM IS APPARATUS MASS,G                                            ZRV005
      WRITE (6,2056)                                                    ZRV005
 2056 FORMAT (7X,'BELT',12X,'OIL',11X,'WATER',8X,'THROUGHPUT')          ZRV005
      WRITE (6,2057)                                                    ZRV005
 2057 FORMAT (6X,'SPEED',9X,'RECOVERED',6X,'RECOVERED',6X,'EFFICIENCY') ZRV005
      WRITE (6,2070)                                                    ZRV005
```

```
 2070 FORMAT (5X,'(KNOTS)',8X,'(GPM/FT)',8X,'(GPM/FT)',7X,'(PERCENT)')  ZRV005
      WRITE (6,2060)                                                   ZRV005
C     B IS FELT THICKNESS,CM                                           ZRV005
C     RKB IS FELT PERMEABILITY,CM**2                                   ZRV006
C     EPSB IS FELT POROSITY                                            ZRV006
C     RHOB IS FELT DENSITY,G/CM**3                                     ZRV006
C     H IS ASTROTURF THICKNESS,CM                                      ZRV006
C     RKH=ASTROTURF PERMEABILITY,CM**2                                 ZRV006
      DENEF=EPSH*H+EPSB*B                                              ZRV006
      IF (D0 .LT. DENEF) DENEF=D0                                      ZRV006
C     PB=FELT CAPILLARY PRESSURE,DYNES/CM**2                           ZRV006
C     PH=ASTROTURF CAPILLARY PRESSURE, DYNES/CM**2                     ZRV006
C     G=GRAVITY ACCELERATION, CM/SEC**2                                ZRV006
      G=981.                                                           ZRV007
C     ALP IS COLLECTOR SHIELD ANGLE, RADIANS                           ZRV007
C      S IS CONTACT LENGTH, FT                                         ZRV007
C   R=AFT PULLEY RADIUS, FT                                            ZRV007
      DO 400 J=3,11                                                    ZRV007
C     V IS SKIMMER SPEED, KNOTS                                        ZRV007
      V=J                                                              ZRV007
  401 FORMAT ('      ***********SKIMMER SPEED=',E12.5,'***********')   ZRV007
      ZH=-PH/G/RHO/H+(RHOB*B+RHOH*H)/H/RHO+RM/H/RHO+                   ZRV007
     1FEE*(EPSB*B+EPSH*H)/H                                            ZRV007
      TCONH=RKH*G/EPSH/(1.-FEE)/RHO/H                                  ZRV008
      ZB=-PB/G/B/RHO+(RHOB*B+RHOH*H)/B/RHO+RM/B/RHO-                   ZRV008
     1H*(1.-EPSH)/B+FEE*EPSH                                           ZRV008
      TCONB=RKB*G/EPSB/(1.-FEE)/RHO/B                                  ZRV008
      GEE=R6.8*V*V/R+G                                                 ZRV008
      TW=R/1.688/V*ALP                                                 ZRV008
      T=S/1.688/V                                                      ZRV008
C     THIS IS SATURATION TIME FOR ASTROTURF                            ZRV008
      THS=RHO*EPSH*H*(1.-FEE)/RKH/G/(2.*ZH+EPSH*(1.-FEE)-1.)           ZRV008
  200 FORMAT ('     T=',E12.5,'     THS=',E12.5)                       ZRV008
      IF (THS .LE. T) GO TO 300                                        ZRV009
      RLB=0                                                            ZRV009
      TH=T                                                             ZRV009
      TAUH=TCONH*T                                                     ZRV009
  301 FORMAT (' THS .GT. T, SO FELT ABSORBS NO OIL')                   ZRV009
      RLH=0.5*(TAUH*(EPSH*(1.-FEE)-1.)+                                ZRV009
     1DSQRT((TAUH*(EPSH*(1.-FEE)-1.))**2+8.*ZH*TAUH))                  ZRV009
      QUANT=(1.-FEE)*EPSH*H*RLH                                        ZRV009
  320 FORMAT (' RLH=',E12.5,' RLB=',E12.5)                             ZRV009
  441 FORMAT (' QUANT=',E12.5,' D0=',E12.5)                            ZRV009
C     CHECK TO SEE IF WE'VE CREATED OIL                                ZRV010
      IF (D0 .GE. QUANT) GO TO 420                                     ZRV010
C     IF D0 .LT. QUANT, ALL OF THE OIL IS IN ASTROTURF                 ZRV010
  422 FORMAT ('  D0 .LT. QUANT; REVISE CALCULATION,AVOID CREATING OIL') ZRV010
      RLH=D0/(1.-FEE)/EPSH/H                                           ZRV010
      WATER=EPSH*H*(1.-RLH)                                            ZRV010
      GO TO 421                                                        ZRV010
  420 WATER=0.                                                         ZRV010
C     IF THERE'S MORE OIL THAN ASTROTURF CAN ABSORB, ASTROTURF         ZRV010
C     ABSORBS NO WATER                                                 ZRV010
  421 DW=0.232*WATER                                                   ZRV011
      XI=-PH/RHO/GEE/H                                                 ZRV011
      TAUW=RKH*GEE*TW/EPSH/RHO/H                                       ZRV011
      R1=XI/RLH                                                        ZRV011
```

```
      R2=TAUW/RLH                                                       ZRV011
  230 FORMAT (' XI=',E12.5,' TAUW=',E12.5,' R1=',E12.5,                ZRV011
     1' R2=',E12.5)                                                     ZRV011
      IF (R1 .GE. 1.) GO TO 23                                          ZRV011
      ITER=1                                                            ZRV011
      X1=R1+0.05                                                        ZRV011
   21 F1=1.-X1+R1*DLOG((R1-1.)/(R1-X1))-R2                              ZRV012
      DF1=-1.+R1/(R1-X1)                                                ZRV012
      X2=X1-F1/DF1                                                      ZRV012
      DIFF=DABS(X2-X1)                                                  ZRV012
      ITER=ITER+1                                                       ZRV012
      X1=X2                                                             ZRV012
      IF (DIFF .LE. 0.005) GO TO 20                                     ZRV012
      IF (ITER .LE. 25 ) GO TO 21                                       ZRV012
   22 FORMAT ('  ITER=',I3,' X1=',E12.5,' RLW=',E12.5)                 ZRV012
      GO TO 99                                                          ZRV012
   23 RLW=RLH                                                           ZRV013
      GO TO 24                                                          ZRV013
   20 RLW=RLH*X1                                                        ZRV013
  213 FORMAT (' ITER=',I3,' X1=',E12.5,' RLW=',E12.5)                  ZRV013
  900 FORMAT ('  ',2E12.5)                                              ZRV013
   24 CONTINUE                                                          ZRV013
  302 FORMAT (' JOB ABANDONED')                                         ZRV013
      QWREC=24.86*DW*V                                                  ZRV013
      QOREC=24.86*V*(1.-FEE)*(EPSB*B*RLB+EPSH*H*RLW)                    ZRV013
  850 FORMAT (1X,'QWREC=',E12.5,5X,'QOREC=',E12.5)                      ZRV013
      THRUEF=4.02*QOREC/DENEF/V                                         ZRV014
  851 FORMAT(1X,'THRUEF=',E12.5)                                        ZRV014
      WRITE (6,2055) V,QOREC,QWREC,THRUEF                               ZRV014
 2055 FORMAT (4(3X,E12.5))                                              ZRV014
      GO TO 400                                                         ZRV014
  300 RLH=1                                                             ZRV014
C     FOR THIS OPTION, THE ASTROTURF IS SATURATED, SO THE FELT         ZRV014
C ABSORBS  OIL'                                                         ZRV014
  303 FORMAT (' THS .LE. T, SO FELT ABSORBS OIL')                       ZRV014
      TH=T-THS                                                          ZRV014
      TBS=RHO*EPSB*B*(1.-FEE)/RKB/G/(2.*ZH+EPSH*(1.-FEE)-1.)            ZRV015
  304 FORMAT (' TB=',E12.5,'TBS=',E12.5)                                ZRV015
      IF (TBS .GT. TB) GO TO 305                                        ZRV015
  310 FORMAT (' TBS .LE. TB, SO FELT IS SATURATED')                     ZRV015
      RLB=1                                                             ZRV015
      GO TO 500                                                         ZRV015
  305 CONTINUE                                                          ZRV015
  307 FORMAT (' TBS .GT. TB, SO FELT IS NOT SATURATED')                 ZRV015
      TAUB=TCONB*TB                                                     ZRV015
      RLB=0.5*(TAUB*(EPSB*(1.-FEE)-1.)+                                 ZRV015
     1DSQRT((TAUB*(EPSB*(1.-FEE)-1.))**2+8.*ZB*TAUB))                  ZRV016
  800 FORMAT (' RLB=',E12.5,' RLH=',E12.5)                              ZRV016
  500 QUANT=(1.-FEE)*(EPSB*B*RLB+EPSH*H*RLH)                            ZRV016
  508 FORMAT ('     QUANT=',E12.5)                                      ZRV016
  502 FORMAT ('    DO .LT. QUANT; REVISE CALCULATION,AVOID CREATING OIL')ZRV016
      IF ( DO .GE. QUANT ) GO TO 501                                    ZRV016
      BQUANT=(1.-FEE)*EPSB*B*RLB                                        ZRV016
  509 FORMAT ('    BQUANT=',E12.5)                                      ZRV016
      IF ( DO .LE. BQUANT) GO TO 503                                    ZRV016
      RLH=(DO-BQUANT)/EPSH/H/(1.-FEE)                                   ZRV016
  505 FORMAT (' DO.GT.BQUANT;SOME OIL IS IN ASTROTURF')                 ZRV017
```

```
      W=EPSH*H*(1.-RLH)                                                 ZRV017
      GO TO 504                                                         ZRV017
  503 RLH=0                                                             ZRV017
  506 FORMAT (' DO.LE.HQUANT;NO OIL IN ASTROTURF')                      ZRV017
      RLB=DO/EPSB/B/(1.-FEE)                                            ZRV017
      W=EPSH*H*(1.-RLH)                                                 ZRV017
       DW=0.232*W                                                       ZRV017
       GO TO 1024                                                       ZRV017
  501 CONTINUE                                                          ZRV017
  507 FORMAT (' DO.GE.QUANT;CALCULATION STANDS AS IS')                  ZRV018
      W=0.                                                              ZRV018
  504 CONTINUE                                                          ZRV018
  513 DW=0.232*W                                                        ZRV018
      XI=-PH/RHO/GEE/H                                                  ZRV018
      TAUM=RKH*GEE*TM/EPSH/RNU/H                                        ZRV018
      R1=XI/RLH                                                         ZRV018
      R2=TAUM/RLH                                                       ZRV018
       IF (R1 .GE. 1) GO TO 1023                                        ZRV018
      IF (R2 .LT. 3.) GO TO 2020                                        ZRV018
      X1=R1                                                             ZRV019
      GO TO 1020                                                        ZRV019
 2020 ITER=1                                                            ZRV019
      X1=R1+0.05                                                        ZRV019
 1021 ARGUM=DABS((R1-1.)/(R1-X1))                                       ZRV019
      F1=1.-X1+R1*DLOG(ARGUM)-R2                                        ZRV019
      DF1=-1.+R1/(R1-X1)                                                ZRV019
      X2=X1-F1/DF1                                                      ZRV019
      DIFF=DABS(X2-X1)                                                  ZRV019
      ITER=ITER+1                                                       ZRV019
      X1=X2                                                             ZRV020
      IF (DIFF .LE. 0.005) GO TO 1020                                   ZRV020
      IF (ITER .LE. 25) GO TO 1021                                      ZRV020
      GO TO 99                                                          ZRV020
 1023 RLW=RLH                                                           ZRV020
      GO TO 1024                                                        ZRV020
1020  RLW=RLH*X1                                                        ZRV020
1024  CONTINUE                                                          ZRV020
      QWREC=24.86*DW*V                                                  ZRV020
      QOREC=24.86*V*(1.-FEE)*(EPSB*B*RLB+EPSH*H*RLW)                    ZRV020
      THRUEF=4.02*QOREC/DENEF/V                                         ZRV021
  514 FORMAT (' QW=',E12.5,' QO=',E12.5,' THRUEF=',E12.5)               ZRV021
      WRITE (6,2055) V,QOREC,QWREC,THRUEF                               ZRV021
  400 CONTINUE                                                          ZRV021
      IF (MARK .NE. 0) GO TO 904                                        ZRV021
 2305 WRITE (6,2300)                                                    ZRV021
 2300 FORMAT ('  DO YOU WANT ANOTHER CALCULATION')                      ZRV021
      WRITE (6,2301)                                                    ZRV021
 2301 FORMAT ('  FOR A NEW VALUE OF DO OR FEE?')                        ZRV021
      WRITE (6,2302)                                                    ZRV021
 2302 FORMAT ('    TYPE IN YES OR NO, DEPENDING ON WISHES')             ZRV022
      CALL YESNO ('YES',&2303)                                          ZRV022
   99 STOP                                                              ZRV022
      END                                                               ZRV022
```

Program Output Corresponding to Figure C-5, Reference 1

```
TYPE IN FEE, THE RESIDUAL OIL VOLUME/VOID VOLUME
:0.0
 FEE  0.00000D+00
THIS IS THE RATIO OF RESIDUAL OIL VOLUME TO VOID VOLUME
IF FEE=0,THE BELT MATERIAL IS FRESH
OTHERWISE ITS PRESOAKED AND PREWRUNG
  TYPE IN OIL SLICK THICKNESS
:4.0
SLICK THICKNESS= 0.40000D+01CENTIMETERS
```

NO.2 DIESEL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.13505D+03	0.00000D+00	0.80203D+02
0.40000D+01	0.17026D+03	0.00000D+00	0.75834D+02
0.50000D+01	0.20211D+03	0.00000D+00	0.72015D+02
0.60000D+01	0.23197D+03	0.00000D+00	0.68878D+02
0.70000D+01	0.26079D+03	0.00000D+00	0.66374D+02
0.80000D+01	0.28915D+03	0.00000D+00	0.64394D+02
0.90000D+01	0.31738D+03	0.00000D+00	0.62827D+02
0.10000D+02	0.34565D+03	0.00000D+00	0.61581D+02
11000D+02	0.37404D+03	0.00000D+00	0.60581D+02

NAVY SPECIAL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.95948D+02	0.00000D+00	0.56981D+02
0.40000D+01	0.12241D+03	0.00000D+00	0.54519D+02
0.50000D+01	0.14773D+03	0.00000D+00	0.52638D+02
0.60000D+01	0.17204D+03	0.00000D+00	0.51083D+02
0.70000D+01	0.19539D+03	0.00000D+00	0.49730D+02
0.80000D+01	0.21781D+03	0.00000D+00	0.48506D+02
0.90000D+01	0.23926D+03	0.00000D+00	0.47362D+02
0.10000D+02	0.25966D+03	0.00000D+00	0.46261D+02
0.11000D+02	0.27885D+03	0.00000D+00	0.45164D+02

NO. 6 FUEL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.55510D+02	0.00000D+00	0.32965D+02
0.40000D+01	0.64170D+02	0.00000D+00	0.28581D+02
0.50000D+01	0.71742D+02	0.00000D+00	0.25563D+02
0.60000D+01	0.78529D+02	0.00000D+00	0.23318D+02
0.70000D+01	0.84711D+02	0.00000D+00	0.21560D+02
0.80000D+01	0.90406D+02	0.00000D+00	0.20133D+02
0.90000D+01	0.95696D+02	0.00000D+00	0.18943D+02
0.10000D+02	0.10064D+03	0.00000D+00	0.17930D+02
0.11000D+02	0.10528D+03	0.00000D+00	0.17052D+02

Program Output Corresponding to Figure C-6, Reference 1

```
 TYPE IN FEE, THE RESIDUAL OIL VOLUME/VOID VOLUME
:0.0
 FEE= 0.00000D+00
THIS IS THE RATIO OF RESIDUAL OIL VOLUME TO VOID VOLUME
IF FEE=0,THE BELT MATERIAL IS FRESH
OTHERWISE ITS PRESOAKED AND PREWRUNG
  TYPE IN OIL SLICK THICKNESS
:1.22
SLICK THICKNESS= 0.12200D+01CENTIMETERS
```

NO.2 DIESEL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.90988D+02	0.17701D+02	0.99937D+02
0.40000D+01	0.12132D+03	0.23601D+02	0.99937D+02
0.50000D+01	0.15165D+03	0.29501D+02	0.99937D+02
0.60000D+01	0.18198D+03	0.35401D+02	0.99937D+02
0.70000D+01	0.21230D+03	0.41301D+02	0.99937D+02
0.80000D+01	0.24263D+03	0.47201D+02	0.99937D+02
0.90000D+01	0.27296D+03	0.53102D+02	0.99937D+02
0.10000D+02	0.30329D+03	0.59002D+02	0.99937D+02
0.11000D+02	0.33362D+03	0.64902D+02	0.99937D+02

NAVY SPECIAL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.88346D+02	0.18438D+01	0.97036D+02
0.40000D+01	0.11727D+03	0.12293D+01	0.96604D+02
0.50000D+01	0.14591D+03	0.43182D+00	0.96157D+02
0.60000D+01	0.17204D+03	0.00000D+00	0.94479D+02
0.70000D+01	0.19539D+03	0.00000D+00	0.91976D+02
0.80000D+01	0.21781D+03	0.00000D+00	0.89712D+02
0.90000D+01	0.23926D+03	0.00000D+00	0.87597D+02
0.10000D+02	0.25966D+03	0.00000D+00	0.85560D+02
0.11000D+02	0.27885D+03	0.00000D+00	0.83532D+02

NO. 6 FUEL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.55510D+02	0.00000D+00	0.60970D+02
0.40000D+01	0.64170D+02	0.00000D+00	0.52861D+02
0.50000D+01	0.71742D+02	0.00000D+00	0.47279D+02
0.60000D+01	0.78529D+02	0.00000D+00	0.43126D+02
0.70000D+01	0.84711D+02	0.00000D+00	0.39876D+02
0.80000D+01	0.90406D+02	0.00000D+00	0.37237D+02
0.90000D+01	0.95696D+02	0.00000D+00	0.35036D+02
0.10000D+02	0.10064D+03	0.00000D+00	0.33161D+02
0.11000D+02	0.10528D+03	0.00000D+00	0.31537D+02

Program Output Corresponding to Figure C-7, Reference 1

```
TYPE IN FEE, THE RESIDUAL OIL VOLUME/VOID VOLUME
:0.0
 FE    0.00000D+00
THIS IS THE RATIO OF RESIDUAL OIL VOLUME TO VOID VOLUME
IF FEE=0,THE BELT MATERIAL IS FRESH
OTHERWISE ITS PRESOAKED AND PREWRUNG
  TYPE IN OIL SLICK THICKNESS
:1.06
SLICK THICKNESS= 0.10600D+01CENTIMETERS
```

NO.2 DIESEL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.79055D+02	0.17701D+02	0.99937D+02
0.40000D+01	0.10541D+03	0.23601D+02	0.99937D+02
0.50000D+01	0.13176D+03	0.29501D+02	0.99937D+02
0.60000D+01	0.15811D+03	0.35401D+02	0.99937D+02
0.70000D+01	0.18446D+03	0.41301D+02	0.99937D+02
0.80000D+01	0.21081D+03	0.47201D+02	0.99937D+02
0.90000D+01	0.23716D+03	0.53102D+02	0.99937D+02
0.10000D+02	0.26352D+03	0.59002D+02	0.99937D+02
0.11000D+02	0.28987D+03	0.64902D+02	0.99937D+02

NAVY SPECIAL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.77106D+02	0.46122D+01	0.97474D+02
0.40000D+01	0.10198D+03	0.49205D+01	0.96690D+02
0.50000D+01	0.12660D+03	0.50458D+01	0.96023D+02
0.60000D+01	0.15091D+03	0.50177D+01	0.95386D+02
0.70000D+01	0.17490D+03	0.48496D+01	0.94755D+02
0.80000D+01	0.19855D+03	0.45445D+01	0.94124D+02
0.90000D+01	0.22186D+03	0.40961D+01	0.93489D+02
0.10000D+02	0.24483D+03	0.34864D+01	0.92850D+02
0.11000D+02	0.26745D+03	0.26775D+01	0.92208D+02

NO. 6 FUEL OIL

BELT SPEED (KNOTS)	OIL RECOVERED (GPM/FT)	WATER RECOVERED (GPM/FT)	THROUGHPUT EFFICIENCY (PERCENT)
0.30000D+01	0.55510D+02	0.00000D+00	0.70172D+02
0.40000D+01	0.64170D+02	0.00000D+00	0.60840D+02
0.50000D+01	0.71742D+02	0.00000D+00	0.54416D+02
0.60000D+01	0.78529D+02	0.00000D+00	0.49636D+02
0.70000D+01	0.84711D+02	0.00000D+00	0.45895D+02
0.80000D+01	0.90406D+02	0.00000D+00	0.42858D+02
0.90000D+01	0.95696D+02	0.00000D+00	0.40325D+02
0.10000D+02	0.10064D+03	0.00000D+00	0.38167D+02
0.11000D+02	0.10528D+03	0.00000D+00	0.36297D+02

APPENDIX E

PERMEABILITY MEASUREMENT

An experiment was set up to measure the permeability of sorbent felt coupons (EX 1017). The results, expressed in terms of permeability as a function of felt compression ratio were used as input for the mathematical model of the ZRV wringer.

The test apparatus used to measure felt permeability is shown in Figure E-1. It is an adapted "permeameter" by the Soiltest Company. The original device was designed to measure soil permeabilities. The inlet and outlet ports were enlarged because felt is more permeable than soil, and so the flow rates are higher.

Preliminary tests showed pore pressures on the order of 10 psi for the dynamic wringing process. This pressure was applied to force Gulf 64 (used and described in the Stage I Final Report) oil through the felt for a permeability measurement. A flow rate was calculated based on a preliminary value of $8.5 \times 10^{-6} cm^2$ for the felt permeability. D'Arcy's law states

$$Q = -\frac{k}{\mu}\frac{P}{t}A$$

where Q is the volume flow rate through the felt in cm^3/sec,

k is the felt permeability in cm^2 $[8.51 \times 10^{-6} cm^2]$

μ is the oil viscosity in g/cm sec [Gulf 64 has $\mu = 2.68$ g/cm sec @ 70°F]

P is the pressure drop across the felt in $dynes/cm^2$ $\left[10 \text{ psi} = 6.87 \times 10^5 \frac{dynes}{cm^2}\right]$

t is the thickness of the felt in cm [6.35 cm for 5 layers]

A is the cross-sectional area of the felt in cm^2 [$8.56 cm^2$ for 1.3" diameter permeameter]

thus

$$Q = \left[\frac{8.51 \times 10^{6} cm^2}{2.68 \text{ g/cm sec}}\right]\left[\frac{.687 \times 10^6 \text{ dynes/cm}^2}{6.35 \text{ cm}}\right][8.56 \text{ cm}^2]$$

$$= 2.93 \text{ cm}^3/\text{sec}$$

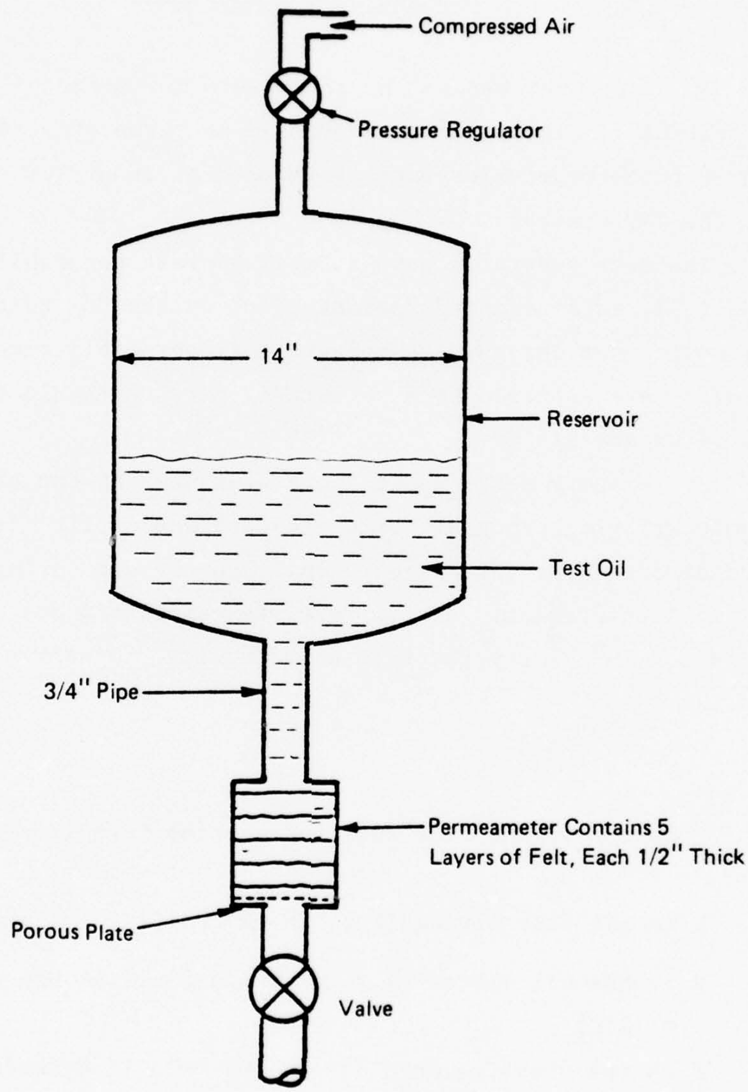

Figure E-1. Permeability Test Apparatus

0796

There are two other system pressures which must be considered: (1) the head of oil in the reservoir, and (2) the pressure drop in the inlet pipe. The hydrostatic head of oil in the reservoir is given by

$$P = \rho g y$$

where ρ = density of oil [0.890 g/cm^3 for Gulf 64]

g = acceleration of gravity [980 cm/sec^2]

y = height of reservoir fill level above felt [15 in.]

Thus $P = 0.892 \text{ g/cm}^3 \times 980 \text{ cm/sec}^2 \times 15 \text{ in} \times 2.54 \text{ cm/in}$

$= 0.33 \times 10^5 \text{ dynes/cm}^2$

$= 0.48 \text{ psi}$

This is less than 5% of the pressure applied to the reservoir surface. The reservoir diameter, moreover, is 14 inches. Thus when 500 ml of oil is drained from the reservoir during a typical run, the liquid level drop is only

$$h = \frac{500}{A}$$

where h = height loss in cm

A = reservoir cross-sectional area $\left[\frac{\pi}{4} (14 \text{ in} \times 2.54 \text{ cm/in})^2 = 903 \text{ cm}^2\right]$

Thus $h = 0.503$ cm and is insignificant.

The pressure drop in the 3/4 in. diameter inlet pipe is given by

$$\Delta p = f \frac{L}{D} \frac{\rho V^2}{2}$$

where f = friction factor $\left[f = \frac{64}{R} \text{ for laminar flow}\right]$

L = equivalent pipe length $\left[6 \text{ in.} + \frac{k_L D}{f} \text{ (factor for gate valve losses)}\right]$[4]

D = pipe diameter [0.75 in.]

ρ = oil density [0.892 g/cm^3 for Gulf 64]

V = oil velocity, cm/sec; $U = \left[\frac{2.93 \text{ cm}^3/\text{sec}}{\frac{\pi}{4} (0.75 \text{ in.} \times 2.54 \text{ cm/in})^2} = 2.99 \text{ cm/sec}\right]$

---

4. R. M. Olson, Essentials of Engineering Fluid Mechanics, 3rd ed. (New York: Intext Educational Publishers, 1973), p. 368.

$$R = \text{Reynolds number} \left[\frac{\rho U D}{\mu} = \frac{0.892 \times 2.99 \times 1.90}{2.68} = 1.89\right]$$

k_L = Resistance coefficient [0.19 for gate valve][4]

Thus $$L = 6 \text{ in.} + \frac{0.19 \times 0.75 \text{ in.} \times 1.89}{64}$$

$$= 6.004 \text{ in.}$$

and $$\Delta p = \left[\frac{64}{1.89}\right]\left[\frac{6.80 \text{ in.}}{0.75 \text{ in.}}\right]\left[\frac{0.892 \text{g/cm}^3 \ (2.99 \text{ cm/sec})^2}{2}\right]$$

$$= 0.108 \times 10^4 \text{ dynes/cm}^3$$

$$= 1.57 \times 10^{-2} \text{ psi}$$

This is quite small compared to the applied pressure of 10 psi.

To minimize edge effects on the oil flow in the felt specimen, a column of felt 5 layers high was used. This ensured that the oil flowed through a nearly constant area of felt in its path through the permeameter. Since this large thickness of felt was used, a run was also made with the pressure at 30 psi, to check the dependency of permeability on flow rate.

The internal resistance of the system to fluid flow includes that created by the porous permeameter plates at the top and bottom of the felt. This resistance is expected to be proportional to the flow rate. Two base runs, one at 10 psi and the other at 30 psi, were made without felt in the permeameter. Flow and system resistance was small.

Further runs were made to determine the effect of compression on felt permeability. The compression ratios used were $\lambda = 0.75$ and $\lambda = 0.50$, corresponding to a 25% reduction in thickness and a 50% reduction in thickness.

Results of these experiments were shown previously in Figure 21.

APPENDIX F

MATHEMATICAL ANALYSIS OF ZRV WRINGER

Skrabak[3] developed a model of the compression of a porous deformable media filled with fluid. This method has been modified to describe pore pressures resulting from wringing the ZRV sorbent belt. A detailed derivation of the governing equation based on Skrabak's model follows first. Then a computer program called "Ringer" is listed which applies this equation to the ZRV wringer problem. The program (1) divides the wringer into increments of length and (2) computes the time invarient pore pressure for each increment. If desired, these pressures can be summed over the wringer contact area to produce a total wringer force and converted into a horsepower component.

Sample output for the computer program follows the listing. The program is conversational and needs little explanation of input data. An option worth noting is related to calculating lower and upper bounds. If the user types in a "o" at the start, the permeability is allowed to vary with compression. If, however, the user types in a "1", the permeability is left at its uncompressed value. The former procedure gives the upper bound on pressure, and the latter procedure affords the lower one.

Derivation of Wringing Pressure

The following derivation of wringing pressures is a translation and simplification of Skrabak's work. The derivation analyzes the one-dimensional, isotropic compression of a porous material saturated with liquid. Figure F-1 shows the physical model being considered along with important dimensions and parameters.

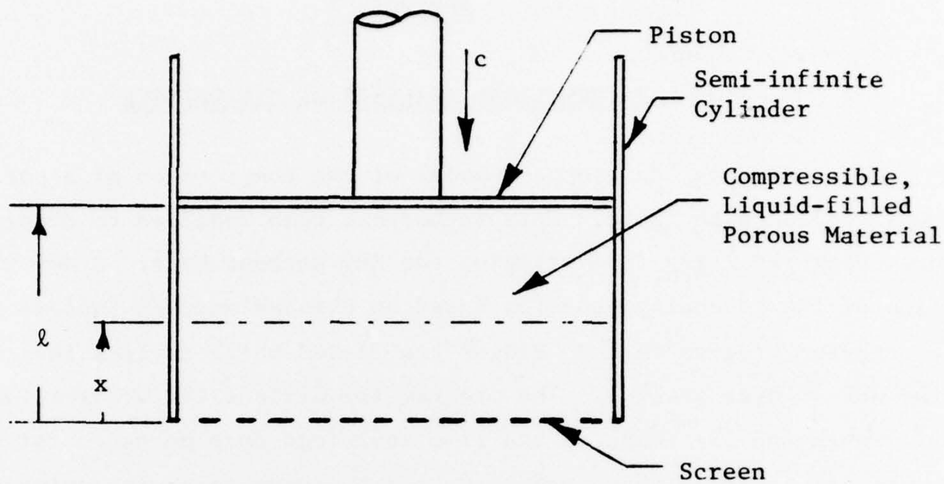

Figure F-1 Compression Model

Symbols

K - Permeability of porous material $\left(m^2\right)$

μ - Dynamic viscosity of liquid $\left(kg\ m^{-1}s^{-2}\right)$

ε - Porosity (void volume/apparent volume) of material

c - Piston speed $\left(ms^{-1}\right)$

ℓ_o - Piston position at start of compression (m)

ℓ - Piston position (m)

A - Piston area $\left(m^2\right)$

λ - Compression ratio $\left(\ell/\ell_o\right)$

a - Constant $(1 - \varepsilon)\ \lambda$

Q_ℓ - Total liquid flow rate $\left(m^3s^{-1}\right)$

q_ℓ - Specific flow rate of liquid $\left(ms^{-1}\right)$

q_s - Specific flow rate of solid $\left(ms^{-1}\right)$

q_r - Relative specific flow rate $\left(ms^{-1}\right)$

q - Total specific flow rate $\left(ms^{-1}\right)$

V - Total cylinder volume $\left(m^3\right)$

V_ℓ - Liquid volume in cylinder $\left(m^3\right)$

V_s - Solid volume in cylinder $\left(m^3\right)$

$\overline{x}$ - Distance through which fluid flows, ℓ-x (m)

x - Position of any location within the porous material (m)

χ - Nondimensional position $\left(x/\ell_o\right)$

v_ℓ - Actual liquid velocity $\left(ms^{-1}\right)$

v_s - Actual solid velocity $\left(ms^{-1}\right)$

v_r - Relative velocity between solid and liquid $\left(ms^{-1}\right)$

P_x - Pressure at any point x $\left(kgm^{-1}s^{-2}\right)$

P_ℓ - Pressure at piston face $\left(kgm^{-1}s^{-2}\right)$

P_o - Pressure at screen $\left(kgm^{-1}s^{-2}\right)$

ΔP - Hydrodynamic pressure loss $\left(kgm^{-1}s^{-2}\right)$

In the apparatus shown in Figure F-1 the volume of the porous medium can be thought of as having two components; V_s the actual volume of the solid, and V_ℓ the void volume which is assumed to be completely filled with liquid. These volumes make up the apparent volume, V.

$$\begin{aligned} V &= A\ell \\ &= V_s + V_\ell \end{aligned} \tag{1}$$

Assuming the solid material is incompressible and does not pass the screen V_s is constant throughout the compression. V_ℓ, however, decreases as the piston progress thus forcing liquid past the screen (assuming the liquid is also incompressible). Porosity ε, defined as V_ℓ/V, also decreased until $V_\ell = 0$ and $V = V_s$. It is useful to note that $\lambda(1-\varepsilon)$ is a constant which will be denoted "a".

$$\begin{aligned} a &= \lambda(1-\varepsilon) \\ &= \frac{\ell}{\ell_o}\left(1 - \frac{V_\ell}{V_o}\right) \\ &= \frac{\ell}{\ell_o}\left(\frac{V - V_\ell}{V}\right) \\ &= \frac{\ell}{\ell_o}\left(\frac{V_s}{A\ell}\right) \end{aligned} \tag{2}$$

$$a = \frac{V_s}{A\ell_o} = \text{constant since } V_s, A, \text{ and } \ell o \text{ are constant.}$$

The porosity can now be expressed as a function of the compression ratio λ.

$$\varepsilon = 1 - \frac{a}{\lambda} \tag{3}$$

Through any cross-section perpendicular to the cylinder axis there is a specific volumetric flow rate q given by

$$q = \frac{cA}{A} = c. \tag{4}$$

Since only incompressible solids and liquids are being considered q is constant with respect to position x. This flow rate can be broken into two components: q_s, due to movement of the solid, and q_ℓ, liquid flow. Obviously $q_s + q_\ell = q$.

At the piston both solid and liquid are moving at the piston speed c and their flow areas are determined by the porosity.

$$q_s\ (x = \ell) = \frac{cA(1 - \varepsilon)}{A} \tag{5}$$

$$= c(1 - \varepsilon)$$

$$q_\ell\ (x = \ell) = c\varepsilon \tag{6}$$

At the screen the solid does not move so

$$q_s(x = 0) = 0.$$

The assumption of isotropic compression implies that the specific solid flow rate q_s varies linearly from $c(1 - \varepsilon)$ at the piston to zero at the screen. Thus at any position x,

$$q_s = c(1 - \varepsilon)\,\frac{x}{\ell} \tag{7}$$

Substituting (3) for ε and defining $\chi = \frac{x}{\ell_o}$

$$q_s = c\,\frac{a\chi}{\lambda^2}\,. \tag{8}$$

Since

$$q_\ell = q - q_s \tag{9}$$

$$q_\ell = c - c\,\frac{a\chi}{\lambda^2}$$

The total liquid flow rate Q_ℓ is given by

$$Q_\ell = q_\ell A \tag{10}$$

$$= cA\left(1 - \frac{a\chi}{\lambda^2}\right)$$

The actual flow area available for the liquid is $A\varepsilon$. Therefore the actual liquid velocity, v_ℓ, is

$$v_\ell = \frac{Q_\ell}{A\varepsilon} = \frac{q_\ell}{\varepsilon} \tag{11}$$

Substituting (10) and (3)

$$v_\ell = c\,\frac{1 - \frac{a\chi}{\lambda^2}}{1 - \frac{a}{\lambda}} \tag{12}$$

$$= c\,\frac{\lambda^2 - a\chi}{\lambda(\lambda - a)}$$

Thus the liquid velocity varies linearly from $v_\ell = c$ at the piston to $v_\ell = c\,\frac{\lambda}{\lambda - a}$ at the screen.

Similarly the solid velocity, v_s, is given by

$$v_s = \frac{q_s}{(1-\varepsilon)}. \tag{13}$$

Substituting (8) and (3)

$$v_s = c\,\frac{\chi}{\lambda}.$$

This relative velocity, v_r, between solid and liquid is

$$v_r = v_\ell - v_s$$

Substituting (12) and (13) and rearranging

$$v_r = c\,\frac{\lambda - \chi}{\lambda - a} \tag{14}$$

Thus the relative velocity changes linearly from $v_r = 0$ at the piston to $v_r = v_\ell$ at the screen.

D'Arcy's law for one-dimensional flow through a porous medium in the range of laminar flow states

$$q_r = \frac{K}{\mu}\,\frac{dP}{d\bar{x}} \tag{15}$$

where q_r is the specific flow rate of fluid through the porous material and $\bar{x}$ is the distance through which the fluid flows. In the case of compressing porous material both solid and liquid are moving and it is their relative flow which produces the pressure gradient $\frac{dP}{dx}$. The relative flow can be expressed in terms of the relative velocity and porosity as in (11).

$$q_r = v_r\varepsilon \tag{16}$$

In Figure F-1 flow moves from the piston toward the screen; therefore $\bar{x} = \ell - x$ and

$$d\bar{x} = d(\ell - x). \tag{17}$$

Noting that

$$\ell - x = \ell_o(\lambda - \chi) \tag{18}$$

and

$$d(\ell - x) = \ell_o\,d(\lambda - \chi) \tag{19}$$

(14),(16), and (19) can be used to rewrite (15) as

$$c\varepsilon\,\frac{\lambda-\chi}{\lambda-\alpha} = -\,\frac{K}{\mu\ell_o}\,\frac{dP}{d(\lambda-\chi)} \tag{20}$$

Rearranging and integrating, (20) becomes

$$\frac{c\varepsilon\ell o\mu}{K(\lambda-a)} \int_{o}^{\lambda-\chi} (\lambda - \chi)d(\lambda - \chi) = -\int_{P_\ell}^{P_x} dP \tag{21}$$

where P_x is the pressure at an arbitrary point x and P_ℓ is the pressure at the piston. After integrating (21) the hydrodynamic pressure loss at x is

$$\Delta P = P_\ell - P_x = \frac{c\varepsilon\ell o\mu\ (\lambda-\chi)^2}{2K(\lambda-a)} \tag{22}$$

The sole condition required to evaluate this one-dimensional problem is that the pressure at x = 0, P_o, is known. In actual practice P_o is usually atmospheric pressure. Evaluating (22) at x = 0 the piston pressure is

$$P_\ell = P_o + \frac{c\varepsilon\ell o\mu\ \lambda^2}{2K\ (\lambda-a)} \tag{23}$$

Substituting (3) for ε

$$P_\ell = P_o + \frac{c\ell o\mu\lambda}{2K} \tag{24}$$

Thus using (3), (22) and (24) the pressure (pore pressure) at any position x within the porous material is given by

$$P_x = P_o + \frac{c\ell o\mu\lambda}{2K} - \frac{c\ell o\mu(\lambda-\chi)^2}{2K\lambda} \tag{25}$$

Program Listing - "Ringer"

```
TOF:
IMPLICIT REAL*8 (A-H,O-Z)
      WRITE (6,201)
      READ (5,200) ICON
  200 FORMAT (I2)
  201 FORMAT (' TYPE IN 1 FOR CONSTANT MATERIAL PROPERTIES')
      WRITE (6,202).
  202 FORMAT ('  TYPE IN BELT SPEED, FPS')
      READ (5,204) VB
  WRITE (6,203)
  203 FORMAT ('  TYPE IN WRINGER LENGTH, FEET')
      READ (5,204) XMAX
  204 FORMAT (F7.2)
      WRITE (6,205)
  205 FORMAT ('  TYPE IN OIL VISCOSITY, CM**2/SEC')
      READ (5,204) RNU
      WRITE (6,206)
  206 FORMAT (' TYPE IN OIL DENSITY, G/CM**3')
      READ (5,204) RHO
      WRITE (6,207)
  207 FORMAT ('  TYPE IN FELT THICKNESS, CM')
      READ (5,204) XLO
RMU=RNU*RHO
A=0.119
PO=14.7
X=0.
3 GW=1.2*DEXP(-0.233*X)
WRITE (6,1201) GW
1201 FORMAT (/,' GW=',E12.5)
GP=-0.0233*DEXP(-0.233*X)
RLAM=(2.*GW/3.)/0.5
IF (RLAM .GE. 1.DO) RLAM=1.
WRITE (6,1202) RLAM
1202 FORMAT (' RLAM=',E12.5)
DY=RLAM/5.
WRITE (6,4) X,RLAM
EPS=1.-A/RLAM
IF (ICON .EQ. 1) EPS=0.881
RK=(2.79*RLAM-1.17)/1.0D5
IF (ICON .EQ. 1) RK=1.62D-5
C=VB*12.*2.54*GP
C2=(14.7*RMU*EPS*XLO*C)/2./RK/(RLAM-A)/1.01D6
WRITE (6,1205) EPS,RK,C,C2
1205 FORMAT ('  ',4E12.5)
Y=0.
2 PY=14.7+C2*(Y*Y-2.*RLAM*Y)
IF (RLAM .GE. 1.DO) PY=14.7
WRITE (6,1) Y,PY
IF (RLAM .EQ. 1.DO) Y=500.
1 FORMAT (' Y=',E12.5,' P=',E12.5,' PSI')
Y=Y+DY
IF (Y .LE. RLAM) GO TO 2
Y=0.
X=X+0.5
IF (X .LE. XMAX) GO TO 3
4 FORMAT (' X=',E12.5,' FT',' LAMBDA=',E12.5)
99 STOP
END
EOF:
*:
```

Sample Input and Output for "Ringer"

```
EXECUTION BEGINS...
TYPE IN 1 FOR CONSTANT MATERIAL PROPERTIES
:0
 TYPE IN BELT SPEED, FPS
:40.
 TYPE IN WRINGER LENGTH, FEET
:5.
 TYPE IN OIL VISCOSITY, CM**2/SEC
:2.7
TYPE IN OIL DENSITY, G/CM**3
:0.97
 TYPE IN FELT THICKNESS, CM
:1.27

GW= 0.12000D+01
RLAM= 0.10000D+01
X= 0.00000D+00 FT LAMBDA= 0.10000D+01
  0.88100D+00 0.16200D-04-0.28407D+02-0.42444D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI

GW= 0.10680D+01
RLAM= 0.10000D+01
X= 0.50000D+00 FT LAMBDA= 0.10000D+01
  0.88100D+00 0.16200D-04-0.25283D+02-0.37777D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI

GW= 0.95058D+00
RLAM= 0.10000D+01
X= 0.10000D+01 FT LAMBDA= 0.10000D+01
  0.88100D+00 0.16200D-04-0.22503D+02-0.33623D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI

GW= 0.84605D+00
RLAM= 0.10000D+01
X= 0.15000D+01 FT LAMBDA= 0.10000D+01
  0.88100D+00 0.16200D-04-0.20028D+02-0.29925D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI

GW= 0.75301D+00
RLAM= 0.10000D+01
X= 0.20000D+01 FT LAMBDA= 0.10000D+01
  0.88100D+00 0.16200D-04-0.17826D+02-0.26634D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI

GW= 0.67020D+00
RLAM= 0.89360D+00
X= 0.25000D+01 FT LAMBDA= 0.89360D+00
  0.86683D+00 0.13231D-04-0.15866D+02-0.32479D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI
Y= 0.17872D+00 P= 0.24037D+02 PSI
Y= 0.35744D+00 P= 0.31299D+02 PSI
Y= 0.53616D+00 P= 0.36486D+02 PSI
Y= 0.71488D+00 P= 0.39598D+02 PSI
Y= 0.89360D+00 P= 0.40636D+02 PSI
```

```
GW= 0.59650D+00
RLAM= 0.79533D+00
X= 0.30000D+01 FT LAMBDA= 0.79533D+00
  0.85038D+00 0.10490D-04-0.14121D+02-0.40969D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI
Y= 0.15907D+00 P= 0.24029D+02 PSI
Y= 0.31813D+00 P= 0.31285D+02 PSI
Y= 0.47720D+00 P= 0.36468D+02 PSI
Y= 0.63627D+00 P= 0.39578D+02 PSI
Y= 0.79533D+00 P= 0.40615D+02 PSI

GW= 0.53090D+00
RLAM= 0.70787D+00
X= 0.35000D+01 FT LAMBDA= 0.70787D+00
  0.83189D+00 0.80495D-05-0.12568D+02-0.53388D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI
Y= 0.14157D+00 P= 0.24331D+02 PSI
Y= 0.28315D+00 P= 0.31821D+02 PSI
Y= 0.42472D+00 P= 0.37171D+02 PSI
Y= 0.56630D+00 P= 0.40382D+02 PSI
Y= 0.70787D+00 P= 0.41452D+02 PSI

GW= 0.47252D+00
RLAM= 0.63002D+00
X= 0.40000D+01 FT LAMBDA= 0.63002D+00
  0.81112D+00 0.58777D-05-0.11186D+02-0.73116D+02
Y= 0.00000D+00 P= 0.14700D+02 PSI
Y= 0.12600D+00 P= 0.25148D+02 PSI
Y= 0.25201D+00 P= 0.33274D+02 PSI
Y= 0.37801D+00 P= 0.39078D+02 PSI
Y= 0.50402D+00 P= 0.42561D+02 PSI
Y= 0.63002D+00 P= 0.43722D+02 PSI

GW= 0.42056D+00
RLAM= 0.56074D+00
X= 0.45000D+01 FT LAMBDA= 0.56074D+00
  0.78778D+00 0.39447D-05-0.99557D+01-0.10894D+03
Y= 0.00000D+00 P= 0.14700D+02 PSI
Y= 0.11215D+00 P= 0.27032D+02 PSI
Y= 0.22430D+00 P= 0.36624D+02 PSI
Y= 0.33644D+00 P= 0.43475D+02 PSI
Y= 0.44859D+00 P= 0.47585D+02 PSI
Y= 0.56074D+00 P= 0.48955D+02 PSI

GW= 0.37431D+00
RLAM= 0.49908D+00
X= 0.50000D+01 FT LAMBDA= 0.49908D+00
  0.76156D+00 0.22242D-05-0.88609D+01-0.19321D+03
Y= 0.00000D+00 P= 0.14700D+02 PSI
Y= 0.99815D-01 P= 0.32025D+02 PSI
Y= 0.19963D+00 P= 0.45500D+02 PSI
Y= 0.29945D+00 P= 0.55125D+02 PSI
Y= 0.39926D+00 P= 0.60900D+02 PSI
Y= 0.49908D+00 P= 0.62825D+02 PSI
-:
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APPENDIX G

EXPERIMENTAL CONFIRMATION OF WRINGER ANALYSIS

Introduction

The dynamic process involved in the ZRV Wringer is a unique combination of fluid flow in a compressible, porous medium. It is not immediately obvious that textbook values of static permeability can be used to get valid predictions of dynamic pore pressures. Thus it is important to validate our adaptation of Skrabak's model for one easily modeled sorbent material. Given adequate experimental verification, then, the analysis identifies important system parameters which characterize the wringing process. The model becomes invaluable in analyzing other belt materials that might become available in the future.

Details of Experiment

A test coupon was made of two 1/2" layers of EX 1017 felt. In the center of the 3-1/2" x 12" coupon was a 1" x 1" hole into which was inserted a compacted lump of solder. After the test coupon had been compressed using the wringer simulator described in Appendix D of Reference 1 the thickness of the lump of solder was measured. This thickness was taken to be the minimum width of the test coupon and hence the minimum wringer gap during the compression stroke. This rather unorthodox measurement procedure was used after dynamic measurements taken with a linear potentiometer were shown in error.

Using a linear cam (for simplicity) on the wringer simulator (see Appendix D, Reference 1), the motor speed was set to compress the felt from 1" to 0.655" in 0.18 seconds. This gave a compression speed c of

$$c = \frac{(1 - 0.655)''}{0.18 \text{ sec}} \times \frac{2.54 \text{ cm}}{\text{in}} = 4.87 \text{ cm/sec}$$

The corresponding wringing force was read from an oscilloscope connected to a load cell mounted on the base of the wringer simulator. The dry test coupon was then cyclically loaded until a constant maximum force was repeatedly attained. For a test coupon of area 32.91 in.^{2} a force of 352 lbs was recorded. Thus the material pressure was

$$P = \frac{352 \text{ lb}}{32.91 \text{ in}^2} = 10.7 \text{ psi}$$

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This pressure was that caused by material deformation alone in the absence of oil.

The test coupon was then saturated with Navy Special Oil having a viscosity of 234 cp at 70°F. When the saturated specimen was subjected to the same deformation described above, the force was 848 lb. This was a total pressure, P, of

$$P = \frac{848 \text{ lb}}{32.91 \text{ in}^2} = 25.8 \text{ psi}$$

Subtracting the material pressure from this one can find the pore pressure on the wringer, P_ℓ, caused by the motion of the fluid:

$$P_\ell = 25.8 - 10.7$$

$$P_\ell = 15.1 \text{ psi}$$

Theoretical Values and Comparison

Skarabak's model gives the following expression for the pore pressure on the wringer:

$$\begin{aligned} P_\ell &= \mu \ell o c \lambda / 2K \\ &= \frac{(2.34 \text{ g/cm}\cdot\text{sec} \times 2.54\text{cm} \times 4.87 \text{ cm/sec } \lambda)}{2K} \left(\frac{14.7 \text{ psi}\cdot\text{cm}^2 \cdot\text{sec}^2}{1.01 \times 10^5 \text{g} \quad \text{cm}}\right) \\ &= 2.11 \times 10^{-4} \ \frac{\lambda}{K} \cdot \text{cm}^2 \end{aligned}$$

At the beginning of compression, $\lambda = 1$ and $k = 1.07 \times 10^{-5}$ cm^2. At the maximum compression, $\lambda = 0.655$. Now, $K = 0.52 \times 10^{-5}$ cm^2 for $\lambda = 0.67$. Without knowing the detailed geometry of the wringing process the expected maximum and minimum pore pressure can be extracted. The higher permeability gives

$$P_\ell = 2.11 \times 10^{-4} \ \frac{.655}{1.07 \times 10^{-5}}$$

P_ℓ = 12.9 psi, while the lower permeability gives

$$P_\ell = 2.11 \times 10^{-4} \frac{0.655}{0.52 \times 10^{-5}}$$

$$= 26.6 \text{ psi}$$

Thus, the experimental value of pore pressure, 15.1 psi, has been bracketed by a maximum of 26.6 psi and a minimum of 12.9 psi. The observed value is closer to the predicted value obtained using the uncompressed value for the permeability. This is due to the difference between test conditions for static permeability measurements and dynamic wringer simulator tests. It is likely that the oil is expelled early on in the compression process, when the instantaneous permeability of the felt is fairly high.

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